THE CIRCULATION AND SLEEP

John F. Shepard

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THE CIRCULATION AND SLEEP

EXPERIMENTAL INVESTIGATIONS
ACCOMPANIED BY AN ATLAS

BY

JOHN F. SHEPARD
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PREFACE

This volume is primarily a report of experimental investigations. Altogether it was necessary to study several hundred records, the total length of which amounted to about thirty-five hundred feet. Each record contained from two to six tracings besides indicator lines. Those reproduced were, of course, selected to show typical conditions.

A part of the expense of employing trephined individuals to serve as subjects, was met by a grant from the Elizabeth Thompson Science Fund. A part of the remainder was paid by the University of Michigan. I am most grateful for these grants. I am indebted to Professors Pillsbury and Lombard for their aid and encouragement at all times, and for reading the manuscript. Thanks are due to Professors G. L. Jackson, F. C. Dockeray, and H. H. Woodrow, and to Mr. C. E. Galloway for assisting in the experiments. I am especially indebted to my wife, who has been of the greatest service in the preparation of the manuscript. Mr. W. C. Hollands has given aid in matters of publication. I wish finally, to express my thorough appreciation of the action of the University in providing for publication.

JOHN F. SHEPARD.

ANN ARBOR, 1913.

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CHAPTER I

THE GENERAL PROBLEM

There have been innumerable speculations as to the nature of sleep, and there are several types of theories which may claim a more or less scientific basis. At present, however, I shall be concerned with the circulatory theories only. I shall begin with a discussion of several important investigations of the relations between sleep and changes in the circulation.

Mosso published his great work, "Kreislauf des Blutes im Menschlichen Gehirn," in 1881. It is based upon a study of three cases, although only a few curves were obtained from each. One was a woman, a considerable portion of whose skull had been removed as a result of syphilitic infection. The second was an epileptic child who had been injured and trephined when eighteen months old. The third was a farmer, trephined on account of injury from a falling brick.

Mosso concludes that in sleep there is relaxation of the vessels of the limbs, shown by plethysmographic tracings from the arm, and decrease of the blood supply to the brain. The heart rate is in general lowered, though subject to great irregularities. A stimulus that does not waken the subject causes a constriction of the vessels of the arm, and consequent increase of flow through the brain. Abdominal breathing is decreased, chest breathing increased. In both waking and sleeping there are undulations in the brain curve, and these are of three types: passive, caused by alterations in general blood pressure, in which there is no change in pulse form; active, due to contraction and relaxation of the brain vessels themselves, in which there is change of pulse form; and another type of passive wave, due to change in venous outflow, in which the pulse at the crest of the wave is restricted, being in this regard the reverse of the first two types.

We shall see later that Mosso's criteria of types of undulation are entirely insufficient. And some of his conclusions in regard to reactions with sleep do not seem to me justified by an examination of his own published curves. I doubt whether the subject was actually asleep during the taking of the records which he gives in Fig. 21, for the recovery from the reaction is altogether too rapid to have accompanied an awakening. Taf. V, 15 and 16, seem much more like accurate plethysmographic tracings that might accompany changes in the depth of sleep, and the subject was definitely snoring; here it will be observed, both a break in snoring and awakening were accompanied by a fall of volume. The falls of volume followed by large pulse in Fig. 26 and Taf. IX, 38, are ambiguous. Some other cases of rise of the brain record with subliminal stimuli, are less open to criticism. The evidence for Mosso's view is very uncertain. It should be added that Mosso himself does not believe that cerebral anæmia is the cause of sleep.

The next year, 1882, Mays published a few records from two subjects. The best curves from one subject seemed to give a fall of the brain volume, both with subliminal stimuli during sleep and with awakening. The result as a whole is uncertain.

The investigations of Leonard Hill were of a different character. He worked almost entirely upon dogs, and in the complete experiment four values were measured: the general arterial pressure, the general venous pressure, the cerebral venous (torcular) pressure, and the intracranial pressure. It was found that the intracranial pressure is in all normal conditions the same as cerebral venous pressure.

Hill found that the amount of cerebro-spinal fluid normally present is small, and the amount of blood in the brain must remain in all physiological conditions very nearly the same (Monro-Kellie doctrine). On this basis he criticises any method of studying the blood supply to the brain with an open cranium, since this changes the physical condition of the cerebral circulation, exposes the cerebral capillaries to the air pressure, and permits alterations of blood volume. The vaso-motor center and all the known nerve supply to the carotid and vertebral arteries were stimulated without furnishing any evidence of vaso-motor control within the brain circulation. Instead, the cerebral venous pressure always varied absolutely with general venous pressure and proportionately with arterial pressure. Sleep, with its lowered blood pressure, he concludes is always due to cerebral anæmia, accompanied perhaps by venous congestion; and the blood pressure, in this process, is controlled by the degree of splanchnic constriction maintained by the vaso-motor center.

Later I shall return to the question of vaso-motor nerve supply to the cerebral vessels and the control of the circulation through them. But the criticism of other methods of investigation and the adequacy of Hill's method demand some consideration here. I have no doubt of the correctness of the Monro-Kellie doctrine within limits. Consequently we shall agree that any large constriction or relaxation of the small arteries of the brain (more than the supply of cerebro-spinal fluid) must involve a change of opposite character in other arteries within the skull or more probably in the venous system,—a readjustment of the relative capacities of the vessels. Now, so far as there is such readjustment it is true that the reaction does not involve exactly the same effect as a vaso-motor response in another part of the body, in the hand for instance. The latter would mean a change in the total capacity of the circulatory system, a rise or fall of the total arterial-venous pressure; the former simply a change in the ease of passage from arteries to veins. But a constriction of the small arteries in any organ, particularly in the brain, must cause a much greater increase in resistance than could be compensated for by expansion of the larger veins by the same volume; and relaxation of the small arteries within any reasonable limits, gives a greater reduction of resistance than decrease of the large veins by a corresponding volume could possibly equalize. As a result, the readjustment brings with it an alteration of the flow, which is all that one could mean by control of the brain circula-

tion. Even if large changes in total blood volume in the closed cranium are impossible, practically the same effect is possible. To trephine the skull and increase the change of volume directly, does not modify the character of the reaction studied, though it may alter its degree somewhat by making unnecessary the comparatively unimportant counter-effect upon the venous system. I am not sure whether Hill thinks of it in this way, but it is an error to interpret the Monro-Kellie doctrine as though it practically necessitated that the cerebral vessels be passive, an error which is often made.

Furthermore, in several records which I shall reproduce later in this work, and in scores of others which expense prevents my reproducing,[1] the brain shows very marked expansions and contractions without in any way plugging the trephine, or interfering with its free pulsations and changes of volume by pressing against the bone or the skin covering. There is room in the normal human skull for very significant reactions without noticeable encroachments upon other vessels. Whether this space is, in the closed cranium, occupied by cerebro-spinal fluid or soft-walled veins, makes no difference.

The objection that investigations recording volume changes through a trephine are invalidated because the opening allows the atmospheric pressure to act upon the cerebral vessels, is a more obvious error The atmospheric pressure is always acting upon the brain through the veins of the neck, in which the resistance of the jugular is negligible. Otherwise such trephined cases as those I have studied would be subject to an unbearable pressure from without. In fact, Hill's own measurements would be impossible, since what his tracings show is how much the intracranial pressure is *more than* the atmospheric pressure.

All things considered, it seems to me that a record of the brain volume combined with a tracing of general arterial pressure, and in some cases a venous pulse, is much the most accurate method for studying the cerebral circulation. To take a curve of intracranial pressure or torcular pressure is analogous to investigating the responses in the arm by means of the pressure in the axillary vein, adding the general arterial and venous pressures in each case. Such curves would be simply inaccurate criteria of the amount of outflow,—the more inaccurate the less the resistance between the vena cava and the vein recorded. A direct determination of inflow or outflow would be preferable.

The best worked out anæmia theory of sleep is that of Howell. This investigator succeeded in recording the changes of volume of the arm, during the whole of a four or five hour period of sleep. He showed that the arm undergoes a gradual expansion during the first hour or more, remains stationary for some time, and then gradually contracts; this contraction becomes rapid about a half hour before awakening. There are minor variations in the curve.

Howell interprets this result in relation to the work of Kohlschütter, Michelson and others, who have shown that the curve of depth of sleep falls for the first hour or two, rises rapidly during the next half hour, and then more slowly during

[1] Likewise in those published in "Organic Changes and Feeling," *Am. J. of Psy.*, 1906.

the remaining hours until awakening. Now we may suppose that the cells of the cortex are fatigued during waking hours, and the vaso-motor center especially is subject to fatigue, although it is kept active by the play of stimuli upon it. Such fatigue causes a tendency toward vaso-motor relaxation, and withdrawal from stimuli hastens this. The relaxation affects primarily the vessels of the skin and lowers the blood pressure; which, according to the usually accepted theory of the passive condition of the cerebral vessels, leads to lessened flow through the brain, especially the small vessels of the cortex; and this is the immediate cause of sleep, and explains its sudden oncoming over the whole cortex. The vaso-motor center is supposed to relax for an hour or two, and then remain in this state for some time, because of its fatigued condition. The cells of the cortex regain their excitability more quickly, hence the earlier rise of the curve of depth of sleep.

More recently, Brush and Fayerweather have studied the blood-pressure at frequent intervals during a period of sleep. They find that the pressure is always lowered, and follows a course more or less parallel to Howell's plethysmographic curve. Their results consequently suggest Howell's explanation. The theory is certainly attractive, but we shall have occasion to criticize it later.

The work of Brodmann points to a different conclusion. By a method similar to Mosso's, he investigated a person of rather low intellectual condition, who had been trephined on account of intracranial pressure. He finds the brain and arm independent of each other, both in total volume and in undulations. There is an increased tendency toward large fluctuations when the subject is sleepy. In going to sleep, the record showed an increase of volume of the brain, and usually of the arm, an increase in the brain pulse, and in the breathing wave in the plethysmogram. Subliminal stimuli during sleep give, according to his results, a rise of volume of the brain. Quiet awakening, without psychical disturbance, is accompanied by a more or less permanent fall of volume of the brain, and no permanent change in the arm curve. But an emotional disturbance has more influence on the result than the process of awakening, and causes a vaso-dilation which may be succeeded by a constriction in the brain after the emotional effect has ceased.

We shall find later that some of Brodmann's conclusions are probably correct, but his curves cannot be accepted as adequate evidence. Some of the reactions are of doubtful significance. They may be due to such physiological factors as the Traube-Hering wave. This is true of the undulation in the first part of curve 137 *a*.

A still more prominent source of error is movement. All changes of position of the subject, even the movements of breathing, are liable to influence the scalp. Anything that alters the tension of the scalp causes violent changes in the plethysmographic record, which have nothing to do with the circulation. In my own work, the detection and elimination of the effects of movement were difficult problems. In curves as short as those of Brodmann there is still more chance of confusion. All of his significant tracings are more or less ambiguous on this

account. Curves 91, IV *b*, 163 and 161, seem to me entirely obscured. Even 156 is rendered somewhat doubtful, although this is at least as good as any curve in the literature.

All things considered, it is impossible to draw any definite conclusion from the literature as to anæmia or hyperæmia during sleep. Brodmann's curves, particularly no. 156, suggest an increased blood supply to the brain; and a critical study of Mosso's records does not conflict with this result. But we cannot set aside at once the belief of Hill that the cerebral vessels are merely passive; and if this is true, the work of Howell and others would make probable a reduced brain circulation. The anæmia theory is very plausible, and is the usual assumption. Furthermore, both the curves of Brodmann and those of Mosso are subject to the confusing influence of movement; and many reactions are of doubtful significance because of their small size or ambiguous relations. Lastly, no published tracing covers a long enough period of time to give an adequate picture of the changes that go with sleep. We need to study several factors in the circulation process on the same individual, and for a longer continuous period of time; and the individual should be normal in his general physical and mental condition.

General Description of Method

Two subjects were used in the principal work of this investigation. The first was the same man who served for the study of "Organic Changes and Feeling," published in Vol. XVII of the *American Journal of Psychology*. He had met with an accident which necessitated the removal of a piece of the skull on the right side near the Rolandic region. The area removed was of irregular shape, with diagonals six and eight cms. in length. No plate was used. The wound had healed well, and at the time the earlier work was begun, the patient had worked in Ann Arbor over two years without inconvenience. He was a laborer of at least average intelligence, and was normal and healthy. The hair was thinner on the scalp covering the trephine, and there was a considerable dip or hollow at that place. The scalp forming the floor of this dip could be felt to pulsate.

Experiments on sleep were carried on with this subject during a part of two school years. Since the study of reactions in the waking state had preceded, he was already thoroughly familiar with the apparatus and surroundings. Consequently, it required only a few nights for him to become used to sleeping under test conditions. He went to sleep easily, and his whole attitude was as though he were taking his regular rest at home. The experiments were usually begun from 7 to 9 P.M. and continued several hours, sometimes all night.

The second subject was a senior student in the university. He had taught school before coming here, and was a man of more than average ability. When a child, he had been kicked in the face by a horse. The skull had been broken, and the physician had removed an irregular piece about 2 by 4 cm. in area, in the right side of the forehead. The injury healed well. At the time of the experi-

ments, the skin was loose and free in its movements over the trephine, and the pulsations were often large.

On account of his different habits, the work was usually begun rather later at night than in the case of the first subject It lasted from two hours to all night (seven hours) according to circumstances. Some other tests, such as the effect of artificial variations of breathing, were carried on either in the afternoon or in the early part of the evening. The experiments were conducted from one to three periods a week throughout the greater part of one school year and a summer school. At first, naturally, he found it difficult to go to sleep in the strange surroundings, and knowing that he was being studied. But soon everything became a matter of regular routine, and sometimes it was difficult for him to keep awake until the apparatus was ready, except on one or two occasions when he was not well.

Other subjects, including myself, were used in several minor experiments.

This investigation includes a study of the volume of the brain and the periphery (hand or foot), of the breathing, of blood pressure, of the heart rate and the time of transmission of the pulse wave over the body, of the jugular pulse, and of the pulse form and size. All these were studied, not only singly and during ordinary sleep, but in combination, and under various conditions designed to show the causes of the reactions found. The details of the apparatus and methods, and the minor experiments to test special points will be described under these headings. I will begin with a general explanation of the recording apparatus and the arrangements.

The kymograph used in all the work was the complete Zimmermann pattern, with Hering slide and writing plane. An additional tin plate was attached to the top of the metal writing-plane. This made possible the use of papers much wider than the drums, and enabled me to record several tracings simultaneously.

With the first subject, the brain circulation curve was obtained as follows. The capsule of a large tambour was taken, wide enough to rest on the edges of bone on both sides of the trephine. This capsule was covered with thin rubber. A piece of cork cut to fit the dip over the trephine, was fastened to this rubber by means of beeswax. A strong cloth bandage was then tied firmly around the head from front to back. From this, another broad bandage was passed over the trephine to the opposite side. The hair was parted away from the dip (shaving the head was entirely unnecessary), the capsule was inverted and the rounded cork placed in the cavity. This done, the broad top bandage was pulled firmly but not too forcefully, down upon the instrument and tied. The capsule was then connected by a rubber tube to a piston recorder. We shall speak of this as the first form of brain plethysmograph. Several were made, in order that if one were leaking, it could be replaced without great delay.

To get the curve from the second subject, two forms of brain plethysmographs were used about equally. One was like that designed for the first subject, except that a circular band of cork was fastened to the edge of one side of the capsule. This band was thicker at its middle than at its ends, and served to make the instru-

ment set evenly on the bone around the trephine. The other form was more analogous to that used by Mosso and Brodmann. A plaster of Paris cast was made from the subjects' forehead. On this a shallow, hard rubber cup was built, covering the position of the trephine. A metal tube led out through the top side of the cup, and a rubber tube connected this to a piston recorder. The edge of the cup was of soft rubber. When this was covered with vaseline, and pressed steadily against the forehead, it formed a small, perfectly air-tight chamber over the opening in the skull. We shall speak of this as the second form of brain plethysmograph. Only a single broad bandage tied around the head from front to back, was necessary to hold either form in place on the second subject.

Two breathing tracings were usually recorded, one from the chest, the other from the abdomen. A Sumner pneumograph connected to a Marey tambour was used for each. In all breathing curves, the fall is due to inspiration, the rise to expiration.

It will be noticed that all brain tracings were written by a piston recorder. In fact, all pulse records, whether from the brain or elsewhere, were made by means of this instrument. The form used was a modification of that described by Lombard and Pillsbury in Vol. III of the *American Journal of Physiology.* As in their work, the piston was made of plaster of Paris. But the ball and socket joint did not work satisfactorily for me. A slight inequality in the weight of opposite sides of the piston, due to a difference in absorption of oil, a particle of dust or a bubble of air in the oil, seemed sufficient to cause the piston to tip and bind. It would often catch if the change of volume moved it much above or below the level line, probably because the oblique position of the piston rod pressed it towards one side of the tube. Whenever the piston began to tilt for any reason, the immediate increase of friction would nearly always aggravate rather than correct the difficulty. To prevent this, I cemented the piston-rod firmly into the center of the piston. Under these circumstances the disk could be cut even thinner than that used by Lombard and Pillsbury. It was made just small enough in diameter to turn almost or quite over in the tube without binding. With this arrangement there was a slightly greater chance that a sudden change of pressure would force a bubble of air past the piston and produce an artificial rise or fall. But such an event seldom occurred, particularly when a somewhat thicker oil was used; and in any case, the experienced observer could easily detect it.

Several recorders were made, of different sizes, ranging from four mm. to eleven mm. in the diameter of the piston. Kerosene was used with the smaller sizes and kerosene mixed with a thicker oil for the larger. When new pistons are made, it is well to keep them for a time in oil.

With one of the recorders, I used a phosphor-bronze writing lever made by Lombard and Pillsbury. For the others, I made levers of thin celluloid. This material seems to me to meet the requirements more fully than the bronze. The lever was cut and bent so that when suspended on the pin used as axis and without the piston-rod attached, it would balance. When connected for use, therefore, the weight of the oiled piston and piston-rod tended to cause the

writing-point to fall. This prevented, to a considerable extent, the leakage of the oil down the sides of the tube, and also diminished the extra movement due to momentum from the strong upward thrust at the beginning of the pulse-beat.

When the instrument is set up for use, and the lever is raised to a level position, it should be so adjusted that the piston-rod will lean slightly toward the writing-point. This arrangement makes the average position of the rod more nearly upright, since it swings away from the writing-point with either an upward or downward movement.

It is practically impossible to prevent a little oil from running down the glass. This sometimes collects on the somewhat narrowed bottom of the barrel, and, on account of the surface tension, acts as a sort of plug and interferes with the waves of air pressure reaching the piston. To prevent this, a fine wire was bent into the bottom of the barrel and served to lead the oil down into the larger rubber tube where it could do no harm.

In all the experiments the subject and the operator were in different rooms. Both were dark rooms. A table was placed in the operator's room near the wall between the two rooms. On this were the kymograph and recording apparatus, the syringes and attachments used to regulate the recorders, and other apparatus necessary for the special experiments to be described later. On several standards nearby were hung enough smoked papers to last during the night's work. On the opposite side of the wall, in the sleeper's room, was placed another table. The bed was next to this. The bed was furnished with all necessary bed-clothes, so that the subject could undress and sleep as usual. There was a hole leading through the wall between the two tables. Through this hole passed the tubes connecting the various plethysmographs, pneumographs, etc., to the recording apparatus. Through this also passed the electric wires for signal keys, a large tube that served for communication between an assistant in the sleeping-room and the operator, and wires for an electric light in the sleeping room so that it could be controlled by the operator. This light was always turned off while the experiment was in progress, except when it was used for a stimulus. What space was left through the hole was packed with cloth.

I was the operator in all except the few tests in which I myself acted as subject. In all except a part of the experiments during the summer school on the second subject, I was assisted by someone who understood the general method of work. At first the assistant only entered the bedroom when something was wanted. But in most of the experiments, he was seated at the table, near the head of the bed, so that he could easily reach the subject to give stimuli, and could report the condition of the subject and the apparatus with the least possible disturbance. To enable the assistant to see to make notes, and when necessary, to see the subject, a very small, shaded electric light was placed on his table. It was operated by a storage battery, and the circuit was closed by a noiseless key at his side. This light was turned on only when needed, the room being kept in complete darkness as much as possible. Even when in use, it was so located that the rays did not strike the eyes of the subject. The assistant and operator could communicate if desirable, by means of the large tube spoken of above.

Two electric indicators wrote on the drum. One was controlled by a key on the operator's table, and was used by him to mark the points on the record at which notes were taken. The other served a similar purpose for the assistant. A thermometer was kept lying on the table, and record was made of all significant changes of temperature. Also all disturbances, stimuli, etc., were carefully noted. All curves are to be read from left to right.

A careful introspective report was taken from the subject after every experiment, and usually whenever he awoke during an experiment. He was asked to tell how he seemed to have slept; whether he remembered anything of disturbances, stimuli or any previous awakenings, and what he could recall of dreams. These and all other notes, with the numbers indicating the place on the record to which they referred, were written on the back of the appropriate papers after the papers had been dipped.

CHAPTER II

THE VOLUME OF THE BRAIN AND OF THE PERIPHERY, AND THE BREATHING CURVE

Method

It has been noted already, that movement is one of the most prominent sources of error in plethysmographic work on the brain. It obscured many of the results of Brodmann and it was particularly troublesome in my work on the first subject. By movement I mean the direct action of contraction of the voluntary muscles on the tracing. Even the interference with inflow and outflow by contraction of the neck muscles cannot be neglected. But the most frequent and most important effect is due to change in position of the scalp. Anything that increases the tension of the scalp over the trephine will raise it out of the dip and cause an apparent increase of volume. When the bandages are applied as they were with the first subject, any movement that raises the scalp will raise the bandages, lessen the pressure on the brain plethysmograph, and produce an apparent fall of volume. For, although the edge of the plethysmograph tambour is forced against the bone around the trephine, the firmness with which this position is maintained may vary appreciably.

Several series of experiments were performed to show the effects of movement. In the first, an assistant placed his fingers at the sides of the trephine, and pulled the scalp away from or pushed it towards the opening. In the second, he moved the region of the bandage around the head. In the third, at a signal from the operator, the subject raised or lowered his eyebrows, and moved his scalp voluntarily in known ways (so far as he could). In the fourth set, a control plethysmographic curve from the scalp was recorded along with the brain tracing. A second instrument like that used over the trephine, except that the cork was flat, was placed in an analogous position under the same bandage on the other side of the head. It was likewise connected to a piston recorder. The circulatory changes in an area of the scalp similar to that affecting the brain curve, were thus recorded. Also any movement of the bandage affected this second instrument even more than that over the trephine, since it partly rested on the cork, and the bone under the scalp caused every change of position to be fully transmitted to the recorder. With the instruments on, the subject lay down on the bed, and pulled his head towards his body or pushed it from his body, according to a signal from the operator. He was then allowed to go to sleep, and tracings from both instruments and from the pneumographs were made.

In a fifth set of experiments, an additional arrangement was used. A square wooden frame holding a plate of glass was taken, and pieces of rope were attached

to the corners. These ropes were made of equal length, and tied to another rope which dropped from the ceiling. This gave a swing which, because it was suspended by a single cord, could be moved easily in any direction. A pillow was placed on the glass plate, and the edges of the frame prevented it from slipping off. The whole was hung about an inch from the head of the bed, and at such a height, that when the body of the subject was lying on the bed, he could comfortably rest his head on the pillow. Some tests were made in which the subject moved his head in various directions while in this apparatus. Furthermore, records of the changes during several hours of sleep were made, and the most perfect sleep curves from the first subject were obtained in this way. Of course, both brain and scalp tracings were written in all these different kinds of tests.

The results of the various series of studies were as follows. When the assistant pulled either scalp or bandage away from the opening, the tracing leaped upward sharply as expected; when he pushed toward the opening, the tracing fell. When the subject raised his eyebrows, the curve fell; when he lowered them, the curve rose. In the fourth series, pushing the head from the body gave an immediate rise in both records, more in the one from the scalp than in that from the brain; pulling the head toward the body gave a fall in both records, more in the one from the scalp. All these changes of level showed an abrupt break in the pulse beat with which they began, such as one would probably never get with true circulation reactions. When the subject tried to contract his muscles gradually, the break was much reduced or absent. But whether the changes were sudden or gradual, they were not accompanied by the variations in the size and form of the pulse, which usually characterize vaso-motor or blood pressure responses.

In Fig. 1 (Plate I) I reproduce a small extract from the sleep curves taken in the fourth series. The tracings in order from the top down are: the abdominal breathing, the indicator (signal) line, the chest breathing, the scalp curve, and the brain record. Periods of relatively shallow breathing and considerable snoring alternated regularly with periods of deeper breathing and no snoring. At *a* occurred such a break in the breathing. There is a large respiration wave in the scalp and brain curves. The fall in the scalp curve goes with the inspiration, the rise with the expiration. This is shown by measurement on other parts of the record where the rate of rotation had been made faster and the drum had been stopped and the exact positions of the needles marked, so that the phasic relation could be made out. The brain curve shows the same correspondence except that often the rise and fall begin and end more gradually and a little earlier than the same events in the scalp curve. The wave in the scalp record is due almost entirely to movement; that in the brain record is obviously in part the same, but we shall find it is also in part, a true physiological change.

At *a*, movement with the break in the breathing caused irregularities which are partly common to the two tracings. In the brain curve, the effects of movement are compounded with other changes which we shall discuss later. All through it

will be seen that movement does not influence the brain record so much as that from the scalp. At other times, its effect was greater than in the part reproduced. At still other times, when the instruments were tied on more firmly, the effect was decreased, the brain pulse was larger and apparently more perfect. In any case, the factor of movement must be reckoned with, and its elimination is often difficult.

In the fifth series this elimination was practically accomplished. Quick movements by the subject caused a temporary disturbance of the record; slow movements gave nothing. Portions of the sleep curves taken under the conditions of this experiment will be reproduced later. It will then be seen that the effects of movement are at least reduced to a minimum.

For some of the experiments on sleep, the apparatus was still further complicated. A second kymograph was placed horizontally a little below the level of the swing and on that side of it opposite to the bed. The axis of the drum was perpendicular to the edge of the swing. A flexible needle was attached to the swing so that it would write on the drum. In this way a record was obtained of the movements of the swing. It was found that in sleep the subject draws his head towards his body during inspiration, and pushes it from his body during expiration. The usual movement was about four mm. This accounts for the large respiratory wave in the scalp and brain records when the swing was not used. Such a peculiar movement in its various relations would probably repay more study than I have given it.

Tests carried out on the second subject showed that movement played a less important part than in the case of the first subject It was necessary to use the swing to eliminate it when he was lying on his side or on his face. But when he was lying on his back, its influence was seldom marked, because of the position of the trephine, no doubt.

The curves taken from the scalp as described above show also that the circulation in the scalp, although it gives a tracing, is negligible so far as its influence on the brain record is concerned.

The peripheral volume recorded was either from the foot or from the hand. The principle of the Hallion-Comte plethysmograph was used. But I found that camera bulbs, of a size and weight which experience had shown to be adapted to the work, gave better results than bulbs usually made for the purpose. Two or three fingers and sometimes the thumb served for a hand curve. For the foot, the bulb was applied at the side just above the heel. Such an arrangement may be influenced by movements whenever the subject is disturbed. And it does not include all of any part of the body, so that some of the record desired is lost. Other plethysmographs get rid of these troubles with greater or less success. The finger-plethysmograph, when properly suspended, is the most perfect form, and was used in a few experiments. But it is inconvenient in work on sleep, and others are worse. They are a continual source of disturbance to the subject. The bulb gave a fairly true tracing except when movement came in, and such places can, in general, be easily detected. The complete continuity of the peripheral

record was often lost, but this was less important than the convenience of the subject which made possible a perfect brain curve. So the bulb arrangement was used.

The pistons of the recorders used in writing the curves were of three sizes, 8.1 mm., 6.5 mm., and 4.6 mm. in diameter. The distance from the axis to the tip of the needle used with the large piston was 12.3 cm.; the distance from the axis to the point of attachment of the piston-rod on the same needle was 2.3 cm. One of the medium pistons was connected to a needle on which the distance from the axis to the tip was 8.7 cm., the distance from the axis to the insertion of the piston-rod was 1.25 cm. The other medium pistons were used with needles on which the first measurement was 10 cm., the second was 2 cm. The actual movement of the piston of the large recorder would, therefore, be given approximately by dividing the movement of the writing-point by 5.3. The same value for the first of the medium recorders would be given by dividing the movement of the point by 7; and the divisor for the other recorders would be 5. These facts will be made use of to express the actual change of volume recorded by the instruments.

Results with the Subject Lying on his Back

The volume was studied during the waking condition before sleep, in going to sleep and during sleep, at awakening and after awakening. This was done while the subject was lying on his back; when he was lying in other positions; when he was sitting propped up in such a way that his legs and hips rested on the bed, while his body leaned against a support covered with bedding, and inclined at an angle of about fifty degrees with the plane of the bed; and when he was sitting up leaning forward against a support. Studies were also made on the influence of interference with the jugulars and with the carotids; on reactions to stimuli when awake; on the effect of artificial variations of breathing; and on the curve of drowsiness when the subject was sitting up and when he was lying down. These topics will be taken up in order. I shall turn now to a description of a few typical records taken when the subject was lying on his back. Illustrations taken from different parts of a single period of work are in some ways of more value than those selected promiscuously from various times. I begin with a series of extracts from the work of February 20, 1906, on the first subject, J.

J., February 20, I, no. 1 (Fig. 2, Plate 2).—This record commenced soon after the lights in the sleeping room were turned out, and while the subject was still awake. The curves in order from the top down are the abdominal breathing, the indicator line, the chest breathing, the tracing from the scalp, and that from the brain. This arrangement will be found in all the extracts from February 20, 1906. Also in all records from that date, the brain volume was written by the large piston recorder, in which the piston was 8.1 mm. in diameter, and the movement of the writing point equaled the movement of the piston multiplied by 5.3.

The scalp record was written by the first medium recorder, in which the index of magnification was 7. The complete apparatus for detection and elimination of movement was used.

The subject was awake, although sleepy at the start. He went to sleep gradually, and was asleep at the end of this extract. At *a* the drum was stopped an instant to give lines of reference for a comparison of the curves. *b–c* represents the level line of the brain recorder, to which, by taking account of the movement of the needle in an arc, all points of the curve may be reduced for accurate measurement. The temperature was falling in the bedroom, which caused a contraction of the air in the tubes and a gradual fall of the scalp tracing. In spite of this, however, the brain curve rose between two and three centimeters as the subject went to sleep. The size of the brain pulse did not change greatly; on the average it was perhaps slightly increased. Under *d*, the scalp record was raised artificially; under *e*, the brain record was lowered to prevent their interference with each other.

A marked breathing wave was coming into the brain curve, as the subject began to sleep soundly near the end of the selection. This could not be due to movement, since the scalp tracing shows that movement was eliminated by use of the swing (compare Fig. 1 and discussion of movement). There was some evidence of the breathing wave in the early part of the record, when the subject was awake, but it became much greater as the subject went to sleep and the volume rose. It is shown in the scalp record mainly by change in size of the pulse.

It will be seen also that there was a noticeable, longer fluctuation in the volume of both brain and scalp at the beginning of the curves. This is usually called the Traube-Hering or Sigmund Mayer wave. As the subject went to sleep, it became much more prominent, particularly in the brain. Measurement from the lines of reference at *a* shows that these waves were very nearly, if not quite, parallel in time of occurrence in the two curves; but the variations in size were by no means parallel in the two.

The breathing changes as sleep came on were characteristic. The abdominal tracing was much reduced. In both chest and abdomen there appeared a somewhat irregular alternation of shallower breathing, accompanied by more or less snoring, and deeper breathing accompanied by a break in the snoring. Measurement from *a* shows that, in general, the decreased breathing corresponds to a rise in volume, the increased breathing to a fall in volume. The increase in breathing often begins a little before the decrease in volume. These relations are not so obvious in the minor, shorter waves as in the larger ones. So we see the Traube-Hering wave of the waking condition gradually changed into a wave with accompanying respiratory changes in sleep. It should be remarked that the shallow breathing was not always accompanied by noticeable snoring. Snoring is shown in the tracing by the check and irregularity in the inspiratory fall of the chest curve.

There were significant changes in pulse form in this and the other records, but these will be discussed later.

J., February 20, I, no. 2 (Fig. 3, Plate 1).—This was a later portion of the same record. Its diameter was reduced one half in the reproduction. It began with a period of decreased breathing and snoring. Corresponding to this, the brain volume was rising; throughout the preceding part of the record, the brain showed a large fluctuation corresponding to the variations of breathing, and this rise was a section of such a fluctuation. The breathing wave in the brain and scalp curves was even greater than in the first extract, and, although the scalp record shows that this might be slightly due to movement, such effect of movement was negligible. A period of increased and free breathing accompanied by a fall of brain volume followed. This, in turn, was followed by three restricted breaths and the beginning of a rise in volume. Then the subject was touched lightly by the assistant. The mark indicating the touch was a little late, since the assistant had to return to his seat to press the key after giving the stimulus. The result was increased and free breathing in both chest and abdomen, and a marked fall in the volume of the brain. The breathing change began at very nearly the same time as the volume change. Then followed a period of decreased breathing and rising volume until near the end of the section. A temporary break in breathing accompanied by a short decrease of volume was followed by restricted breathing and rising brain curve at the end. It will be noticed that the breathing wave in the brain very nearly disappeared with the free breathing and fall of volume, and reappeared with the rising curve. It varied analogously in the scalp curve. The regularity of the scalp tracing shows that it is impossible to explain any of these changes by movement, and they must represent reactions in the cerebral circulation.

J., February 20, II, no. 1 (Fig. 4, Plate 3).—More than half an hour had elapsed since the taking of I, no. 2. Four stimuli, which disturbed the subject slightly but did not awake him, had been given. All resulted in a similar fall of volume. Two of these falls were of much longer duration than that published in the preceding extract, and required three or four times as long a recovery period.

This section is selected as representing in its extreme form another type of the effects of disturbance. *a–b* marks the level line of the brain recorder. The trough of a Traube-Hering wave occurred just at the beginning, and following this, the breathing was restricted and the volume rose. The brain record was so high that the brain and scalp curves interfered with each other; although, on account of its movement in an arc, the brain-recorder lever was writing in front of the other. Just before the mark *c*, the subject's foot, which had been resting on the edge of the bed, slipped off. There was no other disturbance, and the assistant reported that the subject, except for the temporary change of breathing, continued to sleep. There were two deep inspiratory movements followed by lighter and freer breathing for several breaths. The rate of breathing was increased. The brain curve rose, or rather was held up to what had been the highest crest of the breathing waves for about six pulse beats; the pulse was at this point much restricted. The volume then fell to a much lower level, with a pulse as

large or larger than it had been before the disturbance. Over *e* is a change, probably to be correlated with the check in breathing at the same point, but we do not know just how. The scalp curve fell somewhat, and was raised artificially at *d*; and its irregularities show that there was some movement. This movement may have caused slight irregularities in the brain pulse record but was negligible in comparison with the change in the cerebral circulation. The restricted breathing and snoring soon returned and with it the rise in volume of the brain. The respiration wave in the volume, which disappeared during the disturbance, came back with the rising volume.

J., February 20, III, no. 1 (Fig. 5, Plates 4 and 5)[1].—This began about fifteen minutes after the preceding extract. The subject had moved his head slightly once, but there had been no other disturbance, and he had slept continuously except for the alternation of restricted breathing and rise of volume with freer breathing and fall of volume. Such alternation of breathing and volume changes is shown characteristically in the first part of the extract. *a–b* is the level line of the brain recorder. *c, d, e* and *f* designate breaks in the breathing and the accompanying fall of volume. At *4* the subject also moved his head slightly, which gave a somewhat greater fall of volume. The phasic relation of the breathing and volume changes can be more clearly made out from records which were taken to study the pulse-rate and transmission time, and which will be discussed later. But it can be determined with a reasonable degree of accuracy from the curves now being considered. At *g* and again at the end of the section, the drum was stopped for a moment to allow the needles to write lines that would denote their relative positions. Then by a method to be described in more detail later, points in the brain tracing were reduced to corresponding points on the level of *a–b*; and a celluloid square, one edge of which moved along the indicator line, was used to compare the breathing curve with these reduced points. It was found that the beginning of freer breathing is almost simultaneous with the suppression of the breathing wave in the volume, or may occur a couple of pulse beats before the change in the brain; but the brain curve is usually held high from four to eight pulse-beats longer before the real fall of volume begins. The size of the pulse at this high position is often less than at a similar level of volume during a period of restricted breathing.

The scalp tracing shows that movement had some effect at times in spite of the swing. (On account of the faintness of the tracing, the first part of this curve did not reproduce well.) Similar effects of small degree can in some cases be made out in the brain curve, but they are too small and temporary to be of importance.

This record shows how large the breathing wave in the volume may become during the periods of restricted breathing and snoring. The restricted respiration is also the slower; the freer is the more rapid.

At *5* the assistant started to awaken the subject. There was very little movement and practically no disturbance of the curves by movement. During awaken-

[1] On account of the length of this record, it was necessary to reproduce it in two parts.

ing the amplitude of breathing was much increased in both chest and abdomen. Later, when the subject was more completely awake, the amplitude of the chest movements became reduced again, the abdominal movements remained large. Since the rotation of the kymograph is probably approximately constant, the change in rate of breathing can be expressed with some accuracy in terms of the average length of breath in centimeters. We find that during the periods of restricted breathing in sleep, the breaths averaged 0.58 cm. in length; with periods of freer breathing in sleep, the length averaged 0.5 cm.; at awakening, the average length was 0.45 cm.; when the subject was more completely awake, it was 0.47 cm. The rate of respiration was therefore increased more at awakening than at periods of freer breathing in sleep, and persisted more than the increase in amplitude in the chest.

With awakening, the volume of the brain was decreased to a point less than at any time during sleep, and it remained low as long as the subject was awake. The size of the pulse was likewise lessened. There was still a respiration wave in the brain, but it was very small compared with that in sleep. The breathing wave also disappeared from the scalp tracing. Just as the assistant started to awaken the subject, a rise in volume with restricted breathing was beginning. It was checked by the awakening, but perhaps the trough under *h* corresponds approximately to what would have been the position of the next fall with freer breathing. At any rate, the fluctuation of volume with accompanying breathing changes of sleep, was succeeded by a much smaller Traube-Hering wave in the waking condition.

When the subject was awake, the lights were again turned out and he was allowed to go to sleep once more. This he did gradually, and was sleeping fairly well at the end of the record. The temperature of the rooms was falling, so that the scalp tracing sank slowly and was raised artificially once. In spite of this falling temperature, the brain volume increased regularly and constantly. The size of the pulse also became greater. The changes in cerebral volume and size of pulse were so marked, regular and sustained, that this record shows almost perfectly the whole process of awakening and going to sleep again. In the course of a few minutes, the abdominal breathing curve became of less amplitude, and then periods of still more reduced abdominal breathing and irregular and restricted chest breathing began to be succeeded by freer and larger breathing movements in each. Corresponding to this, the Traube-Hering wave in the brain gradually became the fluctuation of volume with periodic change of breathing. At first in this fluctuation, the increase in breathing sometimes seemed to precede the beginning of the fall of volume; sometimes the fall of volume seemed to begin before the increase in breathing; but it is difficult to be entirely certain of the exact relation. The large breathing wave in the volume returned as sleep came on.

J., February 20, IV, no. 1 (Fig. 6, Plate 6).—This record is reproduced in order to show the phasic relation between the breathing curve and the breathing wave in the brain curve. The rate of rotation of the drum was increased so that

it would show the details of pulse form and the interrelation of the tracings. At *a* the kymograph was suddenly stopped, and the needle allowed to describe arcs of reference. The rate-control was changed to its original condition and the drum suddenly started again. The subject was sleeping soundly. It will be seen that the breathing wave with the slow rate was much like that in the preceding curves. Measuring back from the arcs of reference, it is found that the beginning of the rise from the trough of volume *b* occurs a little more than half way down the fall corresponding to inspiration in the chest breathing curve. The beginning of the fall from the crest *c* is on the expiratory rise in the breathing tracing, and about one-fourth the distance from the top. The troughs *d* and *f* correspond to points somewhat more than two-thirds the distance down the inspiratory falls. And the fall from the crest *e* begins about one-fourth the distance from the top of the expiration. .

The beginning of each pulse-beat in the scalp curve was carefully marked under a magnifying glass. A celluloid straight-edge was laid along the record and the troughs marked by an *L*. It will be seen that the breathing-wave in the scalp is considerably delayed beyond the corresponding brain record, even beyond the turning points in the breathing.

J., February 20, IV, no. 2 (Fig. 7, Plate 7).—Only a short space is omitted between no. 1 and this. The record shows the same fluctuations of breathing and volume that were found in the previous charts. As before, the beginning of freer breathing nearly coincides with the cessation of the large respiratory wave in the brain, but the brain volume remains level or even increases several pulse-beats before the fall begins. It will be noticed that during the periods of restricted breathing the inspirations are greater than the expirations, so that the subject holds himself more and more in the condition of inspiration; with the freer breathing, the subject quickly returns to normal. These statements are not true of all such fluctuations, but they are true of a considerable part. The period of free breathing at *a* is quickly succeeded by rather irregular and restricted breathing. The brain volume rises to a high level at first, and shows comparatively little fall afterwards. Possibly one might interpret such a case as a simple tendency toward increase of volume, if comparison with the usual waves did not show that it is merely an abbreviated reaction.

At *4* the assistant started to awaken the subject. There was the usual increase in depth of both chest and abdominal breathing, followed by a decrease in the chest when he was more nearly awake. The average length of respiration was 0.7 cm. during restricted breathing, 0.48 cm. during the increased breathing at awakening, and 0.5 cm. afterwards. As before, there was a decrease in the brain volume and to some extent in the size of pulse. The respiratory wave was almost eliminated, and the Traube-Hering wave became very small. The scalp tracing shows that at *b* there were two temporary effects of movement of considerable size, but they had proportionally small influence on the brain record.

When the drum was stopped, the subject said he remembered of being awakened before, but remembered nothing else since he went to sleep.

November 14, III (Fig. 8, Plate 8).—This is an extract from a record taken before the swing was constructed. It is therefore subject to the effects of movement. The brain curve is at the bottom, and comparison with the charts we have already discussed shows that a considerable part of its respiratory wave was probably due to movement. It was written with a large recorder. The hand tracing is next above. It will be seen that the hand volume also showed a considerable respiratory wave. The chest breathing curve is just below the indicator line (the abdominal is not recorded). At *a* the light was turned on, and at *b* the assistant disturbed him. Before the stimulus, the breathing had been deep and regular without definite snoring. With the stimulus, it became much shallower; but the change was not sudden as in February 20; the depth gradually became less and then greater again. The rate of respiration was increased temporarily. There was a fall in the volume of the hand, which continued throughout the selection, and the needle had to be raised twice artificially. The respiratory wave in the hand was much diminished. The influence of movement is obvious in the brain curve, but it shows a definite fall, which began to recover earlier than the hand.

In other parts of the same record from which this extract was taken, there are two additional and similar reactions to a stimulus. There is also a rather irregularly periodic decrease and increase of breathing of like kind occurring without stimuli, except that shallow breathing is usually not also faster, may even be slower, and in all these cases, the decrease of breathing corresponds to the rising volume, the increase to the falling volume. In some places this correspondence is not exact, though it is usually quite close.

Fig. 1 (Plate 1).—This has already been described. It remains only to call attention to the fact that accompanying the increase in depth and rate of breathing, the brain volume remained about stationary with cessation of the respiratory wave for a few pulse-beats, and then fell to a distinctly lower level. It began to recover soon afterwards.

H., April 6, I (Fig. 9, Plates 9 and 10)[2] (April 6, 1907).—This record from the second subject commenced soon after the lights in the bed-room were turned out, and while he was still awake. The top curve is that of abdominal breathing, and just below that is the chest breathing. Then follow an indicator line used by the operator, one used by the assistant in the bed-room, and the brain record. The brain volume was written by a medium-sized recorder, in which the piston was 6.5 mm. in diameter, and the ratio of the movement of the piston to movement of the writing-point was 1 to 7. The first form of brain plethysmograph was used on the head. Since tests had shown that movement seldom influenced the curve from this subject appreciably when he was lying on his back, no apparatus for elimination of movement was necessary. *a–b* is the level line of the recorder. The temperature in the sleeping-room was falling a little.

The subject was awake at the start. He went to sleep in a manner characteristic of him and often found in all subjects. Periodic decrease and increase

[2] On account of the length of this record, it was necessary to reproduce it in two parts.

of breathing was accompanied by increase and decrease of brain volume. This periodic change showed equally in chest and abdomen. The decrease in breathing usually came on gradually, the increase was more sudden. The restriction of breathing during the low ebb of each period was very marked, particularly at first. Measurement, after reducing the brain tracing to its level, shows that the increase in breathing begins as a rule somewhat before the fall of volume. The fall in volume was generally much more abrupt than the rise. Under *c* and *d* the brain curve was lowered artificially, 3 cm. or more in each case, to keep the recorder within the range in which it would work most freely. Finally the last restriction of breathing was less extreme and changed gradually into an amplitude of both chest and abdominal movement rather greater than during the waking condition. The assistant reported that at *1* the subject jerked a little, at *2* he was beginning to snore, at *3* he had stopped snoring, and at *4* he was snoring regularly. This snoring was distinct but not particularly labored. The inspiratory fall of the chest breathing shows the check clearly.

Counting the artificial drops at *c* and *d*, it will be seen that the brain volume rose about 6 cm. as the subject went to sleep, and this in spite of a falling temperature. The size of the arterial pulse from the brain was also greatly increased, about doubled.

The breathing-wave which came into the curve as the subject began to sleep regularly was large, although not quite so marked as with the first subject. The pulse was of distinctly smaller size at the trough than at the crest. Towards the end of this extract, the kymograph was run more rapidly. Measurement from the lines of reference would show with great accuracy the phasic relation of the two breathing waves in this portion of the record, and with fair accuracy the relation in the preceding portion. It was found in this way that the trough of the volume wave occurred on or just at the beginning of the check in the inspiratory fall; the crest in the volume wave occurred on the latter half of the expiratory rise, usually near its end.

The real waking condition did not last long enough to study the Traube-Hering wave in it. But the large fluctuation in volume, with accompanying changes in depth of breathing characteristic of going to sleep, became a shallower Traube-Hering wave of similar limits of length during sleep. There does not seem to be any regular change in depth of breathing, corresponding to this Traube-Hering wave. A thin piece of celluloid, on which lines were ruled 1 mm. apart, was laid along the respiratory curve, and the variations in depth of breathing were carefully measured. There was some indication that a slightly reduced respiration occurs in a trough or on a rise of volume, but no relation could be determined with certainty.

H., April 6, II, no. 1 (Fig. 10, Plate 11).—This portion was taken about twenty-five minutes after the preceding one. The drums had been stopped once to change papers, during which time the subject slept evenly. Otherwise a continuous record had been taken. Approximately five minutes before, the subject had ceased snoring, and awakened sufficiently to change his position, although

not sufficiently to recognize stimuli. The disturbance was accompanied by a decrease of volume and size of pulse. This chart begins where the movements ceased, and the subject was going to sleep again. At *3* the assistant noted that he was beginning to snore. Sleep brought with it a rise of volume, and increase in the size of pulse. The respiratory wave in the brain returned, and the Traube-Hering wave seems to be continuous from low-volume to high-volume. The changes in depth of breathing accompanying the fluctuations of volume were small, and measurement from lines of reference in the tracings just after the part reproduced, shows that the increase in breathing occurred either just before, on, or after the crest of volume.

H., April 6, II, no. 2 (Fig. 11, Plate 12).—About ten minutes of record intervened between the preceding extract and this one. The subject slept regularly. Just previous to *4*, a strong gust of wind through the open window awakened him, so that he ceased snoring, and moved. The brain volume was held up with smaller pulse for three breaths, and then fell so low that the recorder had to be raised artificially at the mark "art." The breathing became increased in amplitude and irregular at first, and then decreased in amplitude and rate. The breathing wave in the volume almost disappeared. Somewhat farther along, in a part of the record not reproduced, the assistant spoke and aroused the subject completely. The volume fell about 1 cm. more at that time.

H., January 25, I (Fig. 12, Plate 13).—This record and the others to be reproduced from January 25 and from January 15, were taken from the second subject by means of the second form of brain plethysmograph, and while he was lying down on his back. The brain curve in all was written by the large-sized piston recorder (diameter of piston is 8.1 mm.; ratio of movement of piston to movement of writing-point is 1 to 5.3). This extract does not begin at the beginning of the record. A part is omitted in which the subject drowsed off somewhat and then aroused himself again; the volume rose with the partial sleep, and fell again with the disturbance. So the reproduced portion begins where the subject had just been moving, had adjusted himself and was so drowsy that he went to sleep quickly. As usual, there were several alternations of decreased and increased breathing in both chest and abdomen, with accompanying increase and decrease of volume. The increase in breathing usually began a little before the fall of volume. The last changes from restricted to freer breathing were less abrupt, and the respiration then became more regular, with an amplitude intermediate between the extremes. During the remainder of the chart, in which the subject slept soundly, only small alternations in breathing can be detected, more certainly in the abdomen than in the chest. Measurement from the beginning of the record shows that an increase corresponds to, or begins just before a fall of volume of a Traube-Hering wave.

If we measure the level of brain volume from the bottom of the pulse-beat, we find that the curve rose nearly 4 cm. as the subject went to sleep. The recorder was dropped artificially at the mark "art." With increase in volume, the size of the pulse showed a tendency to increase somewhat at first, but soon

reached a limit and began to decrease; and at the height of volume the pulse was relatively small. The cause of this decrease seems to be a restriction to the rise, and there is a more or less definite line beyond which the curve does not go. Even the general volume would probably have risen farther otherwise. In the Traube-Hering wave there is a small pulse at the crest of volume, a larger pulse at the trough of volume. Towards the end of the extract the volume had fallen a little, and the pulse became correspondingly larger. The respiratory wave in the volume is not so evident as in other records, but it can be followed in an imaginary line connecting the lowest point of the pulse-beats during sleep.

In some records taken under these conditions, the subject slept for some time with periodic variations of breathing and volume like those discussed in previous descriptions. In other records he slept evenly for fifteen minutes or more, with the brain volume uniformly high and pulse small. More often in even, regular sleep, the volume was somewhat lower and pulse larger, as at the end of this extract; the tracings taken just after the part here reproduced show that he continued to sleep with the curve usually at about such a level.

H., January 15, II (*1st. ext.*) (Fig. 13, Plate 14).—This is an extract from a record taken with an arrangement similar to that used in January 25, I. It is reproduced in order to show the appearance of the Traube-Hering wave under these conditions when the subject is sleeping lightly, and with marked periodic variations in depth of breathing. It will be seen that the pulse is large at the trough, and small at the crest of the wave. Furthermore, each wave reaches a limit of height that is almost exactly the same in all. Measurement at the beginning of the original record shows that the breathing curves must be shifted backward about 2 mm. in order that corresponding points of the breathing and volume curves will be in a vertical line. It will then be found that the increase in breathing begins slightly before the fall of volume.

H., January 15, I (Fig. 14, Plate 15).—About twenty minutes of record preceded the portion reproduced, in which the subject had gone to sleep and slept evenly; the volume had risen as he went to sleep, and remained uniformly high with small pulse, except for a shallow Traube-Hering wave. Even this Traube-Hering was practically absent during the last five minutes, in which the subject had snored more definitely. The first of this extract shows a high volume, small pulse, and regular breathing, with a check in the inspiratory fall due to snoring.

Before the experiment began, a key, which was in circuit with the lower indicator, had been placed on a chair beside the bed, and within easy reach of the subject. He was instructed to reach and press the key whenever he realized the he had awakened out of a sleep. The mark at *1* is such a signal. It will be seen that the awakening was accompanied by a greatly increased amplitude of chest and abdominal breathing, and somewhat decreased rate. After the subject was awake, the rate of breathing was not again increased, the amplitude of the abdominal remained larger than during sleep, but the amplitude of the chest became smaller than in sleep. The brain volume at first showed a tendency to rise with very restricted pulse, then fell with increasing pulse to a level more

than 6 cm. lower. At the lowest level, and at the trough of the strong breathing wave which appeared, the pulse was smaller again. The volume reaction began at least as early as the change in breathing.

In view of the discussion of curves which will be given later, it should be noted that when the subject pressed the key, particularly when he began to reach for it as indicated by the change in chest breathing, the brain volume had not shown more than half its total fall. Yet he was well enough awake to remember all about his actions when he awakened again and reported an hour afterward. He must have awakened, realized the situation, and gotten the action under way by this time.

H., January 25, II (Fig. 15, Plate 16).—At the end of the extract from January 25, I, the brain curve had fallen to a point just below its highest level Since that time, nearly an hour, the subject had slept with only one serious disturbance, and the brain curve had otherwise remained in practically the same condition. Such is the state in which we find it at the beginning of this selection. The subject was snoring somewhat, a Traube-Hering wave was traceable in the brain, and the respiratory wave in the volume was fairly large.

Just before *1*, there was a noise outside the building, which disturbed and awakened the subject. The result was an increased and freer breathing; in two places the pneumograph tracing was disturbed by movement; finally, after he was awake, the amplitude of chest breathing became rather less than during sleep, that of the abdomen decreased but remained larger than during sleep. The brain volume increased with smaller pulse for a short time, and then fell with larger pulse to a level between 3 cm. and 4 cm. lower than during sleep; in the last part of this fall, the pulse became smaller with the decreasing volume. The respiratory wave in the volume was reduced.

The subject remained awake, and the drum was run for about five minutes; the experiment was then stopped and an introspection taken. The subject reported that he went to sleep soon after the experiment started. Something (the disturbance spoken of above) half waked him, and he wanted to press the key, but "couldn't bring himself to do it." He then went to sleep again. The next he knew was being awakened by the outside noise, which he heard more as a dream than as a full realization of it.

Result with the Subject Lying on his Side

H., March 7, III (Fig. 16, Plate 17).—In this record the subject was lying on his back, but with his head turned far to the right. He had been sleeping during the last fifteen minutes, with no change in the curve except a periodic increase of breathing, and accompanying fall of volume of a Traube-Hering wave. The chest pneumograph (the lower respiratory curve) was on too loosely, so that it only gave a tracing at the periods of greatest depth of breathing. The second form of brain plethysmograph was used, and was connected to the large piston recorder. At the beginning of this extract, the volume was high and the pulse

small. At *3*, the light in the sleeping room was turned on; at *4* (the mark was a little late), the door into the sleeping room was opened. Both stimuli disturbed the subject and gave an increase in breathing and fall of volume with larger pulse. Under *a* the recorder was raised artificially. At *5*, I spoke to the subject and asked him to wake up but not move. The awakening was accompanied by increased breathing. When he was awake, the breathing decreased again, but not to the degree found in sleep. The volume of the brain fell with a larger pulse. The subject reported, when the drum stopped, that he remembered he was dreaming just before he awoke.

Results with the Subject Sitting Propped Up

The next records to be described were taken when the subject was sitting propped up; his legs lay on the bed; his body and head rested against a support inclined at an angle of about 50° with the bed. All curves from the first subject were obtained by means of the first form of brain plethysmograph, while the second form of brain plethysmograph was used for all those to be reproduced from the second subject.

Tests of the influence of movements in the case of the second subject showed practically no effects. With the first subject, a scalp tracing showed the same fluctuations on account of movements, that were found when he was lying down, only they were not so large in the inclined position. But these changes, except the breathing wave, were usually of a quite different direction from the brain volume change, and were nearly always easily distinguished by their abruptness. Most of the records were unquestionable. Furthermore, it would be difficult to use the apparatus for elimination of movement in this position. It could only be done by suspending it from in front of the subject, and supporting it by a counterbalancing weight. Inasmuch as this would be inconvenient to the sleeper, and everything except the breathing wave was certain anyway, this was considered unnecessary.

J., January 30, III (Fig. 17, Plate 18).—The diameter of this record was reduced one-tenth in the reproduction. The curves in order from the top down are the indicator line, the chest breathing, the hand volume, and the brain volume. The hand curve was written with the first moderate sized recorder, the brain volume was written by the large recorder. The record was begun with the light turned on in the sleeping room, so that the assistant could easily watch the subject through the door. This did not trouble him, and he went to sleep slowly and gradually. About eight minutes of the record is omitted before the beginning of the part reproduced. In this omitted portion, the brain volume rose only slightly; the hand volume rose several millimeters.

At *a*, the rate of rotation was decreased; and in making the change the drum was practically stopped, and caused two marked lines in each tracing, which are useful as lines of reference. At *1*, the light in the bedroom was turned out. At *2*, it was again turned on. At *3*, the assistant entered the bedroom. The subject

was apparently sleeping. At *4*, the assistant came out, and at *5*, the light was turned off. Unlike most experiments, the assistant did not remain in the subject's room during this test. A little later in the record than the part reproduced, the assistant again entered the bedroom. The subject was soundly asleep.

It will be seen that as sleep came on, the brain volume increased one and one-half centimeters if measured from the bottom of the pulse, over three centimeters if measured from the top of the pulse. The size of the pulse from the brain increased much more in proportion to the increase in volume than it did when the subject was lying down. The volume of the hand rose only slightly, and then fell again during the latter part of the record. It showed more violent reactions to disturbances than the brain, although both curves went down at such times. The Traube-Hering wave in the volume became more marked as the subject went to sleep; the accompanying breathing changes were less certain than in other records. Measurement from the lines of reference, and allowing for any change of level, shows that with few exceptions the waves were very nearly parallel in time in the two curves; usually they did not vary from each other by more than two or three pulse-beats. The breathing wave in the volume was small; it became greater in the record following the part reproduced.

The vertical breaks in the tracings are due to folding the original in storing it.

J., February 6, II, no. 1 (Fig. 18, Plate 19).—This is another study of the changes in going to sleep propped up. The tracings from the top down are the indicator, the chest breathing, the volume of the hand, and the volume of the brain.

On account of the expense of publication, about five minutes of the beginning of this record are omitted from that reproduced. In it the brain volume had increased 1 cm. with considerable increase in size of pulse. At *a*, the drum was stopped for a moment, which gives lines of reference. At *b*, the brain recorder was dropped artificially; here also the record is blurred by folding. At *1*, there was a slight noise, and the assistant noted that the subject seemed to be going to sleep. At *2*, he was snoring and sleeping soundly. The volume of both brain and hand increased as the subject went to sleep. The size of pulse from the brain was markedly increased in proportion to the change of volume. The pulse from the hand was not definitely changed. The Traube-Hering wave became fairly marked with oncoming of sleep, and was practically parallel in time in the two curves; it did not always correspond in size in the two. There was a tendency for freer breathing to accompany a fall of volume, but the periodicity in the breathing was not so clear as that in the volume.

J., February 6, II, no. 2 (Fig. 19, Plate 19).—This is an extract selected from the same record, and was taken about ten minutes later. It is given to show the large respiratory wave which had come into both brain and hand curves. The subject's breathing was deep and labored. The volume of brain and hand had not changed materially. A period of freer breathing for three breaths was accompanied by a temporary fall of volume.

H., March 30, I (Fig. 20, Plate 20).—In this and the following records from the second subject, the curves in order from the top down are the abdominal

breathing, the chest breathing, the operator's indicator line, the indicator line used by the assistant in the bedroom and the brain volume curve. The brain volume in this and all similar cases was written by means of the large piston recorder.

At *a* and *b*, the brain recorder was artificially lowered. The subject was awake, but drowsy at the start. He went to sleep quickly. At *1*, the assistant noted that the subject had been moving his body and arms. During the part of the record just after that reproduced, the assistant noted that the subject was breathing deeply and was asleep.

It will be seen that the brain volume rose approximately 7 cm. as the subject went to sleep. It fell temporarily with the disturbance at *1*. At its height in the neighborhood of *b*, this increase of volume reached a line beyond which it could not go; and there was a consequent restriction of pulse like that found in previous records with the same instruments and from the same subject lying down. Near the end of the extract the curve fell again, with increased size of pulse, to a level which was still distinctly higher than that during waking condition. It is approximately at this level that the subject usually sleeps, as we shall find in other records. There is a considerable respiratory wave in the curve at the end. Except for the restriction of the pulse as the volume reaches its limit of rise, the increase in size of pulse was enormous compared with the increase of volume.

H., April 5, II (Fig. 21, Plates 21 and 22).[3]—The subject had slept through the preceding record, about forty minutes in length. He had been aroused and was awake at the beginning of this. At *5*, he moved a little. The fall at *a* was probably partly artificial, in that a bubble of air apparently escaped past the piston. At *6*, he began to breathe more deeply. Before *7* he was snoring perceptibly; then he stopped, then began again. At *8*, he snored more. The fall at *b* was artificial. At *9*, he was snoring loudly and regularly.

At the beginning of the curve there seems to be a line below which the volume cannot fall, the level at which the scalp becomes taut and will not sink further. As in all cases, the volume of the brain increased when the subject went to sleep. Every indication of sleep, as at *6*, brought with it a rise of volume. Every disturbance of sleep, as at *7*, was accompanied by a fall of volume. The curve from *8* through *9* and beyond shows the level at which the subject usually sleeps. A majority of the records taken under similar conditions show this type of curve. With the increase of volume, there was an increase in size of pulse which was very large in proportion to the change of volume

During the first part of this record there was a periodically restricted and freer breathing, which, as usual, accompanied the rise and fall of a Traube-Hering wave in the volume. As sleep became deeper, the average depth of breathing was increased, and the restricted phases became less marked until the periodicity could not be traced with certainty. The wave of volume became a Traube-Hering wave in sleep.

[3] The pulse form was slightly obscured by the necessity of tooling out the engraving, particularly in the first part of the record. On account of the length of this record, it was necessary to reproduce it in two parts.

There was a considerable respiratory wave in the volume during deep sleep. Near the end, the drum was run rapidly for a short distance. Measuring from the ends of this space, it is found that the trough of the volume wave occurred near the end of the check in inspiration due to snoring; the crest of volume occurred in the latter part of expiration.

There is often a sudden fall in the volume, particularly from the crest of a Traube-Hering, which does not involve a break in the pulse like that due to movements. Such a fall is seen at *c*. It is doubtless due to a quick, weak heart-beat followed by a delayed one, such as we shall see much more of in studying the heart-rate changes later. There are in all these records important variations of pulse form which will also be studied later.

H., March 30, II (Fig. 22, Plate 23).—In reproducing, the diameter of this record was multiplied by three-fourths. The subject was asleep at the start, and had been sleeping uniformly at this level for about twenty-five minutes. At *2*, he moved considerably, as shown also by the breathing tracings. He seemed very nearly awake, although he did not remember it when asked to give introspections one-half hour later. At *3*, the assistant noted that he was breathing more regularly again. At *4*, the assistant made a noise and the subject stopped snoring and moved a little afterwards. He then remained practically awake during the following twenty minutes until the drum was stopped (most of which is, of course, not reproduced).

The brain volume fell so much at *2* that I had to raise the recorder twice artificially. It rose again as the subject returned to sleep, and decreased again at *4*. A large increase in size of pulse accompanied a rise of volume. A decrease accompanied a fall of volume.

The breathing was increased with a fall of volume at disturbances. It was less in waking condition than during sleep. The abdominal breathing was deeper, the chest shallower, during the sleep between *3* and *4* than in that at the beginning of the record. A considerable respiratory wave was found in sleep.

H., March 28, I (Fig. 23, Plates 24 and 25).[4]—The diameter of this curve is reduced one-half in the reproduction. The pulse form is therefore obscured; but this will be shown in more detail later.

The subject was very sleepy from the start, and it was reported by the assistant in the bedroom that he nearly went to sleep during the preliminary testing before *a*. And there was, correspondingly, an increase in volume and size of pulse from the brain. At *a*, the drum was stopped, the lights in the sleeping-room were turned out, and the regular test was begun. At *b*, the brain curve was dropped artificially. At *1*, the subject moved. At *2*, there was a slight noise of someone passing outside. At *3* and *4*, the subject moved. At *5*, he snored a little and then breathed more deeply. At *6*, he was sleeping well, not snoring much. At *7*, the clock struck. At *c*, the assistant made some noise in talking through the tube. At *8*, the subject swallowed. At *9*, he was snoring louder. At *10*, there was a noise outside, which disturbed the subject and led to increased and irregular

[4] On account of the length of this record, it was necessary to reproduce it in two parts.

breathing temporarily. At *11*, he had practically stopped snoring. At *12*, there was the light noise of rain outside.

The volume and size of pulse from the brain increased as the subject went to sleep. Corresponding to the rapid oncoming of sleep, the circulation change reached its limit in a comparatively short time. As the volume rose to its limiting line, the size of pulse was again restricted as in the records previously described. This curve illustrates the less usual type of sleep in which the volume tracing is held up near such a limiting line during a great part of the time.

With every disturbance of breathing, with increased and freer breathing, there was a corresponding fall of volume. Measuring from the lines of reference in the first part of the record, it is found that the breathing change usually begins a little before the fall of volume. At every disturbance noted by the assistant, especially *3*, *4*, *8* and *10*, there was such a change in breathing and volume. The fall from the limiting position at *10* shows characteristically an increase and then a decrease in size of pulse. There were the usual reverse changes as the subject returned to deep sleep.

There was not so much snoring and not so large a respiratory wave as usual.

There are several illustrations of the short, weak heart-beat followed by a delayed one, and the accompanying brief fall of the needle, as in the other records. These are seen, for example, before *1*, before and after *2*, and before *3* and *5*.

Results with the Subject Sitting up, Leaning Forward

Several curves were taken from the second subject to find the change in the brain when he went to sleep sitting up, leaning forward, and resting his chin on a cushioned support. In these curves, gravity had an influence similar to that in the records just described; but the brain substance tended to press forward against the skull in the neighborhood of the trephine. Presumably with this arrangement, the changes shown in the tracings would be more completely due to the changes in the circulation in the immediate neighborhood of the trephine, less due to changes in a large section of the cerebrum; the alteration in diameter of the brain as a whole would not exert so much influence. There were some difficulties. The slight pressure of the cerebro-spinal fluid apparently served, with the second form of brain plethysmograph, to make the scalp bulge until it was nearly taut, and thus prevented even the pulse from showing itself accurately. For this reason, the first form of brain plethysmograph was used for all records. The even tension of the rubber in this served to keep the scalp back against the firmer substance, which never protrudes so as to make the skin taut. Furthermore, the position was too uncomfortable for the subject to sleep well. Particularly it was impossible to go to sleep in an adequate apparatus for elimination of movement, and consequently the tracings are not altogether free from the effects of movement.

I shall describe three extracts.

H., August 1, I (Fig. 24, Plate 24).—The diameter is reduced one-half in the reproduction. The chest breathing is at the top; the brain curve is at the bottom.

The breathing curve is somewhat interfered with by striking at the bottom. The subject had been asleep, had been disturbed, and was partially awake at the beginning of the part reproduced. A note made at the beginning of the next paper, at which time the tracing was entirely similar to that at the end of this paper, states that the subject was breathing audibly, as though sleeping fairly soundly. This extract, then, will represent the process of going to sleep.

The volume and size of the pulse from the brain increased. There was a wave in the volume such that a small increase in breathing usually accompanied the fall of volume, but the change in the breathing was never abrupt. The respiratory wave in the volume was probably in part due to the breathing movements.

In other cases the brain volume rose as much or more; but the size of the pulse was sometimes not increased so much, and might even be decreased in the latter part of the rise, although there was no such definite limiting line as was found in previous records with the second form of brain plethysmograph.

H., July 20, II, no. 1 (Fig. 25, Plate 25).—The order of curves from the top down is abdominal breathing, chest breathing, indicator line, and brain plethysmograph. The diameter is reduced one-half. The subject had been asleep, had been disturbed and moved, and this extract begins immediately after the disturbance. The subject was probably partly asleep. As he became quiet and returned to deeper sleep, the brain recorder rose without constant change in size of pulse. It was dropped artificially at *a*. At *b*, a period of deeper, freer breathing was accompanied by a decreased volume and size of pulse. This was followed by a rise of volume and larger pulse as the breathing returned to the sleeping form.

H., July 20, II, no. 2 (Fig. 26, Plate 25).—The diameter of this also is reduced one-half. The subject was partially asleep at the beginning of this extract (about three minutes of record are omitted between no. 1 and no. 2). He began to awaken at *a*. The recorder fell and was raised artificially at *b*. Movement so obscured this and other awakenings under the same conditions that they are not entirely reliable. But the indications are always, as here, that awakening is accompanied by fall of volume, and probably decreased pulse generally.

Compression of the Jugulars

Several curves were taken from the second subject to show the effect of interference with the venous outflow upon the brain circulation. Some were taken while the subject was sitting propped up, others while he was lying down on his back. The former were recorded with the second form of brain plethysmograph, the latter partly with each form of brain plethysmograph. The subject usually compressed the jugulars himself. His fingers were placed over the veins before the experiment began. At a signal from the operator, pressure was applied, at a second signal it was removed. I reproduce two tracings to illustrate the effect.

H., July 17, VII (1st ext.) (Fig. 27, Plate 26).—This was written with the second form of brain plethysmograph while the subject was sitting up. It will

be seen that compression was accompanied by increased volume and smaller pulse. A part of the restriction of pulse was apparently due to reaching a limiting level (on account of the taut scalp and plugged trephine) like that sometimes found in deep sleep. But a comparison of curves under *a* (during normal) and *b* (during compression) at approximately the same level, shows that the decrease was not entirely caused by this process. There was a change in the breathing tracing probably due to the subject's movements in applying and removing compression; it does not occur in many records. The pulse form, which is shown clearly where the kymograph ran more rapidly, will be discussed later. Although the piston recorder did not leak elsewhere in a long series of tests, the sudden fall when compression was removed in this case caused a bubble of air to escape and necessitated the artificial rise under *c*.

H., July 17, VIII (*1st ext.*) (Fig. 28, Plate 27).—This is an extract from a much longer record. It was taken while the subject was lying on his back, with the first form of brain plethysmograph. It represents the end of a period of compression and the return to normal. At the beginning of the extract, the kymograph was running rapidly to show the pulse form. When the pressure was removed, the volume fell. The size of the pulse was not greatly changed, perhaps slightly increased. The pulse form underwent a characteristic change which will be referred to later.

Reactions While Awake

Some years ago I published[5] the results of an investigation of the reactions to stimuli while sitting up during the waking condition. The first subject in the present study served as subject for the section on the brain circulation in the previous work. Since that, tests have been made of the waking reactions of the second subject while sitting up. Also a quite extended series of experiments, mostly on the first subject, have shown the effects of stimuli during the waking condition while the subject is lying down on his back. With the second subject sitting up, no very intense stimuli were tried. All moderate stimuli of every character gave an increase in volume and size of pulse from the brain. Talking and laughing, on account of the irregular breathing, caused an irregular tracing. The experiments were not nearly so thorough as in the earlier work, and the results, so far as they went, were entirely similar to those already published from the first subject. For this reason I shall not reproduce any of them here, but shall turn to a description of a few of the tests with the first subject lying down.

J., January 30, I (Fig. 29, Plate 28).—The chest breathing curve is next the indicator line, the brain curve is at the bottom, and the curve between these two is from the hand. At *5*, the subject attended to a faint watch tick, and attempted to get the attention wave. There was no surprise at the signals to begin and stop, and it required considerable effort. At *6*, the assistant yelled and slammed the door of the subject's room. He was frightened, and did not get over the feeling

[5] "Organic Changes and Feeling," *American Journal of Psychology,* 1906, Vol. XVII, pp. 522–584.

for some time. The attention had no appreciable effect upon the hand volume, but caused a gradual rise of volume of the brain, but with somewhat smaller pulse beat. The brain gradually returned to normal afterward.

The fright was accompanied by a rise of volume of the hand with smaller pulse. After a few pulse beats, this was followed by a brief constriction. The brain showed the same short rise of volume with smaller pulse, followed by a period in which the volume fell part way toward normal, with a size of pulse nearly (but not quite) normal. Volume and pulse then gradually returned to normal.

J., October 22 (Fig. 30, Plate 29).—The chest breathing is at the top, the brain record is next below the indicator line, and a curve from the foot is at the bottom. At *2*, a man walked by the door, but the subject did not pay much attention to him. At *3*, or just before, a whistle was blown. It frightened the subject, although not severely. The result was an increase in volume of the brain. On account of the change in size of pulse accompanying the wave in the volume, it is impossible to be certain whether the reaction caused a variation in size. At any rate, there was no marked effect on the pulse. The foot tracing rose slightly, and then fell considerably below normal. Both curves then gradually returned to normal.

J., December 19, I, Exp. 6 (Fig. 31, Plate 30).—The curves from the top down are the indicator line, the chest breathing, the hand volume and the brain volume. Both systems of tubes were leaking slightly, but not enough to interfere materially with these experiments. At *6*, the assistant made a loud noise, which so frightened the subject that he did not get over it for some time. The volume of the hand increased for a few pulse beats, with a pulse somewhat smaller than normal, then decreased below normal and was raised artificially. The brain volume increased with smaller pulse, then dropped slightly, then rose to an even higher level with a pulse somewhat larger than at first, but yet less than normal. After another undulation the curve returned gradually to normal.

J., December 19, I, Exp. 9 (Fig. 32, Plate 31).—This is a later extract taken from the same series as the preceding one. At *9*, occurred the same sort of fright as at *6*, except that the subject got over it more quickly. The result was a rise in volume of the hand with a smaller pulse, followed by a fall. The brain increased in volume with smaller pulse, and then gradually returned to normal, the size of pulse becoming normal more rapidly than the volume.

J., October 29, I (Fig. 33, Plate 29).—The diameter is reduced one-half. The chest breathing is above the indicator line, the brain curve below it. The curve is slightly marred by the fact that the piston caught in three places, which was due to a particle of dust accidentally dropped into the cylinder. The stimulus at *2* was a secondary circuit through the hand of the subject; an exposed wire was used as an electrode. It pained the subject but did not cause contraction of the muscles of the arm. The breathing became shallower at first, then deeper. The brain increased in volume with somewhat smaller pulse, and gradually returned to normal. It will be noticed that in the Traube-Hering wave, which shows better

toward the end of the extract, the pulse is larger at the crest of the wave than at the trough. This is not the rule, however, with the first subject lying down.

The importance of the pulse form in all these curves will be brought out later.

Effects of Changes in Breathing

Another fact of importance for the interpretation of the sleep records is the influence of artificial changes of breathing. Altogether, I studied the effects, particularly on the brain circulation, of the following conditions:—attempted expiration with closed passages, and attempted inspiration with closed passages; simple holding of the breath in inspiration or expiration; artificial snoring produced either by conscious interference with intake of air, or by interference with both intake and outgo; deep, free breathing; chest breathing as distinguished from natural (chest and abdominal) breathing. The chest breathing and deep breathing were tested mainly with the subject lying down; the cessations of breathing mainly with the subject sitting up in the case of the first subject, lying down in the case of the second; the artificial snoring, both with the subject sitting up, and with him lying down. I shall describe a few typical records.

J., October 12, IV (Fig. 34, Plate 32).—Most of the results with a cessation of breathing were taken early in the course of the experiments when I was still using short papers. I reproduce a paper on which two tests were made. The second one ran by the end of the paper, and so is continued at the beginning; its curves can be traced with ease among the curves of the first test. The markers from the top down were the indicator line, the chest breathing, the hand volume and the brain volume. The record was from the first subject and he was sitting up. At *1*, the subject tried to draw air into his lungs, but held his nose and mouth closed to prevent it. The hand volume seems to be decreased, although the wave in the tracing obscures this; this decrease continues after free breathing begins again. The brain volume is not appreciably affected until near the end of the restricted breathing, when it begins to increase; this increase reaches its crest about four breaths after free breathing returns. The drum was stopped before the tracings had completely returned to normal. At *2*, the subject tried to expire forcibly with similarly closed passages. The result in the hand was a brief rise of volume followed by a fall. In the brain there was a brief rise with larger pulse, followed by a fall toward normal with smaller pulse. Another undulation near the end of restricted breathing (probably a Traube-Hering) was followed by an increased volume and larger pulse during free breathing. Again the tracings had not returned to normal when the drum was stopped. "Art" on the paper signifies an artificial change.

I chose this record for reproduction because it shows both a restricted inspiration and restricted expiration. It should be added that the fall in the hand volume was usually more marked than in this case. Another record of restricted inspiration, in which the effort was probably greater, gave a brief fall in the brain with smaller pulse, then a brief rise with larger pulse, then a reaction similar to that reproduced. Simple holding of the breath was accompanied by

a result very similar to the first test on the paper reproduced. In one case in which the breath was held much longer, the rise in the brain began about the same time after the beginning of the period of checked breathing, reached a relatively high level at the end of that period, and reached its crest at the third breath after free breathing returned. In all rises of volume, the pulse increased in size with rise of volume. Holding the breath gave the same result with the second subject, except that there was a greater acceleration of the rise when he began to breath again.

J., November 28, III (Fig. 35, Plate 33).—This is from a record taken from the first subject. He was lying down on his back with his head resting on a fairly thick pillow. At *4*, deep, slow breathing commenced. The result was a brief rise of volume of both brain and hand, with size of pulse about normal. This was followed by a fall, particularly in the brain. The brain curve had to be raised artificially. The pulse averaged somewhat smaller with the low volume in the brain. The hand tracing soon returned to practically normal. The brain fell a little more even after the close of the part reproduced, and continued low throughout the period of deep breathing.

This record is typical of those of deep breathing taken when the subject was lying down. Others taken when the subject was sitting up show almost no effect upon the volume of either brain or hand, except to cause a large breathing wave in it. But in this case also, if there is any change of level, it is a fall.

To show the effect of artificial snoring, I reproduce the beginning and the end of records of two periods of such breathing from the second subject, and omit the middle portion of each period.

H., July 17, VII (*2d ext.*) (Fig. 36, Plate 34, and Fig. 37, Plate 35).—This was taken while the subject was sitting propped up, and by use of the second form of brain plethysmograph. The chest breathing is at the top, the brain tracing at the bottom. Artificial snoring began at the signal in the indicator line; the resistance was mainly to intake of air. The result was a fall of volume with small pulse. The volume remained at this low-level line all through. The mark in the indicator line in the latter part of the extract, shows where artificial snoring stopped. It will be seen that the subject breathed more deeply during the snoring, and this was followed by a period of reduced breathing. The volume rose to about the former level with larger pulse.

H., July 17, VIII (*2d ext.*) (Figs. 38 and 39, Plate 36).—This was taken by means of the first form of brain plethysmograph, and while the subject was lying down on his back. The conditions were otherwise similar to those in the preceding case, and it needs no further description.

Most of the records with chest breathing as distinguished from natural breathing were clear and unambiguous. But I will reproduce none of them, since they show nothing particularly characteristic, and are so large that it would be expensive to print them. They were taken from the second subject. When, in attempting to breathe more with his chest, the subject increased markedly the total depth

of breathing, the result was a fall of volume of the brain, as in the above cases with the first subject. In other cases there was no appreciable effect.

I regret that no reliable curves were taken with merely slowed and shallow breathing.

Delay of the Circulation Change

I wish now to describe a series of curves bearing upon the temporal relation of the reaction in the brain circulation to the sleep process.

H., January 15, II (2d ext.) (Fig. 40, Plate 37).—This is another extract from a curve which we have already had occasion to discuss in part. Although the volume was so high that the pulse was restricted, the subject was only lightly asleep when this extract began. At *1*, the light was turned on and off. At the drop in the line marked *2*, the light was again turned on, and the assistant entered the sleeping room and spoke to the subject. At *3*, the whistle was blown. The curve is like those in which the subject had his head turned slightly to the left side, and this may have been the case, although the assistant did not report the position of the head at the end of this curve. The fact to which I wish to call attention now is that the light at *1* affected the subject somewhat,—he had some memory of it afterward,—but there was no appreciable effect upon the brain circulation. With the light and entrance of the assistant at *2*, the curve was at first raised slightly (which was partly movement, however) and then fell to a lower level, with larger pulse. The whistle caused a still further fall of volume. That the subject was only lightly asleep at *1* is indicated by the breathing and by the fact that according to his statement at the end, he noticed the light. At *2*, the subject moved and understood what was said to him. That *1* should have caused no reaction, and *2* only a partial reaction which was completed at *3*, suggests that the circulation change may lag behind the mental process.

On several different occasions when the first subject was very sleepy, I placed near his hand a key in circuit with the time-maker writing on the drum. He was asked to sit quietly in the dark, in some cases leaning his head on a support, and allow himself to go as nearly to sleep as possible. Naturally under these conditions, he only lost consciousness a short time before the strain of the position would awaken him. Whenever he realized that he had awakened from even a brief period of sleep or drowsing, he pressed the key, and so indicated that instant on the record. A few records were taken under similar conditions except with the subject lying down. But at these times he usually slept deeply and often forgot his instructions when he did awake. I will describe two extracts from records taken under such conditions, the first when the subject was sitting up, the second when he was resting against a support at an angle of 60° with the bed. The curves from the top down in each are the indicator line, the chest breathing, the volume of the hand, and volume of the brain.

J., November 28, II (Fig. 41, Plate 38).—The subject was very sleepy and would no sooner awake than he would at once start to sleep again. At *a, b, c, d,* and *e*, he pressed the key. At *e*, there was some noise outside and he awakened

with a start and jumped. The position of the jump is indicated by the disturbance in the chest, hand and brain curves; the hand tracing was entirely displaced by the movement, and a little later had to be regulated artificially to prevent its interference with the brain curve. The subject pressed the key soon after the jump. As usual, the volume, especially of the brain, increased as the subject began to sleep, and decreased as he awoke. But if the curves are reduced to the normal level of the needles, and allowance is made for the displacement of the writing-points from vertical as measured by the lines of reference at the beginning and end of each paper (in this case the correction is small), then it will be found that the key was pressed a little (two or three pulse beats) before or just as the volume curves began their descent.

J., December 19, II (Fig. 42, Plate 39).—This is one illustration, typical of those cases in which the subject was leaning back against a support. Otherwise conditions were similar to the above, and it needs no further description. It will be seen again that the subject pressed the key just before the curves began their descent.

It should be added that in a small part of the cases, the key was pressed later, the subject's introspection being that he forgot it at times until a moment had passed. I may also refer again to the description of H., January 15, I, given above.

Summary

I shall not attempt to summarize the results of this chapter in a definite number of concise statements. But I shall give a sort of abstract of what is shown by the records taken to study the volume of the brain and of the periphery and the breathing.

In all positions of the subjects, and whether sleep came on quickly, gradually, or with a series of interruptions, the volume of the brain was markedly increased as sleep came on. Counting the records from both subjects, there were altogether seventeen cases in which the subject went to sleep lying on his back, which are covered by adequate evidence as to when the subject went to sleep, and in which the curves are so nearly perfect that there can be no possible doubt of the result. In each of these there was a definite and significant rise of volume with sleep. There were also many records so obscured by movement, leaking apparatus, or other cause, that no conclusion could be drawn from them with complete certainty. But so far as anything could be said, they indicated a larger volume. In addition, a large number of tracings were made in connection with the study of blood-pressure, etc., to be discussed later, and they uniformly show the same fact. Fifteen clear cases of going to sleep "propped up," and three cases of going to sleep sitting up leaning forward, gave undoubted increase in the brain volume; and several, less perfect, indicated the same result as probable.

One record was taken with the second subject sitting propped up and using the first form of brain plethysmograph. Under these circumstances, the brain substance falls away from the trephine and permits the pressure of the rubber to

hold the scalp taut, except when a rise of volume raises it. Sleep was accompanied by a rise of volume and large pulse.

One case in which the second subject went to sleep lying on his right side, and two in which he was lying on his left, showed a higher brain curve with sleep. There was never a fall in any position.

The absolute values of the majority of volume changes, or the portions of them that affected the region under the plethysmograph, were between 0.3 cu. cm. and 0.7 cu. cm. How much additional change in any case was compensated for by displacement of cerebro-spinal fluid or by compression of veins, it is impossible to say.

There was, in general, an increase in the size of the arterial pulse from the brain, accompanying the increase in volume with sleep. The tendency was to a greater increase in size of pulse in proportion to the increase in volume when the subject was sitting up, than when he was lying down. Both the volume change and the size of pulse are limited by the fact that, particularly with the second form of brain plethysmograph, there is a fairly definite upper limiting line beyond which the curve cannot rise. There is likewise a similar lower limiting line which marks the low level of the curve. As these lines are approached, the pulse must be restricted. These lines probably mark where the scalp covering the trephine becomes taut. When the support underneath is sufficiently removed, which never happened except sometimes with the second subject when he was sitting up, the scalp may be forced in until it is taut. This position is not absolutely definite, since the neighboring scalp can yield somewhat. When the brain begins to even slightly plug the trephine, there is perhaps a local rise of pressure of cerebro-spinal fluid to a certain extent, due to restriction of venous outflow, which causes the scalp to bulge until it becomes taut. Hence the advantage of the first form of brain plethysmograph, in which the tension of the rubber overcame the pressure of fluid, and pressed the scalp back against the firmer substance. The first form of plethysmograph, then, probably gives a more accurate record of the changes in the brain substance itself, free from interfering processes. Even here, there is, under exceptional conditions, as when the second subject leans forward or lies on his face, the possibility of a much less definite limitation of rise by the plugging of the trephine.

Throughout the period of sleep the volume of the brain remains higher than in the waking condition. Stimuli given during sleep, but not strong enough to awaken the subject, usually cause either a fall of volume of the brain with decreased pulse (except as the pulse is modified by removal of the above restrictions) or a level or even slightly raised volume for a few pulse-beats followed by such a fall. There were twenty-one clear cases which were not obscured by movement or other cause, taken when the subject was sleeping on his back; twenty-two such cases were taken when the subject was sleeping propped up; and one was taken when he was sitting up leaning forward. All of these gave the above result. Several others were so obscured by movement that no certain conclusion could be drawn. Three caused the slight rise for a few pulse-beats without being followed by a definite fall.

Waking brings with it a fall of brain volume, and altogether the reverse of the changes brought about by going to sleep. Of cases in which the curves were reliable, fourteen taken when the subject was lying on his back, nine taken when he was sitting propped up, and four taken when he was sitting up leaning forward, all gave a fall. Likewise three cases in which the second subject was lying on his right side, and one in which he was lying on his left, resulted in a fall. Two or three cases showed a short rise preceding the fall. It should be emphasized that there was the same fall even when the subject was awakened with a start by a strong stimulus, although many such records were of course obscured by movement. Those records injured by movement are at least consistent with this conclusion.

I have attempted to study the records taken at different times during the night, to determine whether there is any variation in the volume of the brain that can be correlated with the supposed curve of depth of sleep. I have not been able to arrive at any definite conclusion except that the highest volume, that which with the second form of brain plethysmograph approaches a limiting line, is usually found soon after the subject goes to sleep, and as a rule disappears within fifteen to twenty-five minutes at the most. During the greater part of sleep, the brain curve is at a level a little below this extreme. Of course, when sleep is obviously light, the circulation is more nearly in the waking condition, although sometimes the volume then is higher than one might expect. I have been unable to find any other definite variation of the curve. But the effects of movement and changes of temperature at different places in several records are so great that it is difficult to draw any conclusion on this point.

Neither one of the subjects very often reported a dream. In the two or three cases found, in which the sleeper awakened from a dream and reported it, I noticed that there had been a more or less irregular disturbance (fall and recovery) of the curve for a few minutes before. This suggests that dreams are a disturbance of sleep, and that they are, sometimes at least, rather discontinuous and irregular, more so than the subject appreciates.

Compression of the jugulars while the subject was awake caused a rise of volume of the brain, generally with smaller pulse. Stimuli while the subject was awake caused an increase in brain volume. When the subject was sitting up, this increase in volume was accompanied by a larger pulse. When he was lying down (this applies only to the first subject) the rise in volume was nearly always accompanied by a smaller pulse; in only two or three cases out of thirty was there a slight increase. In reaction to strong stimuli, with which the circulation effects last for some time, it is usually found that when the pulse from the brain at any given level in the earlier part of the reaction is compared with that from a similar level of volume in the later part of the reaction, the pulse in the later part is larger than that in the earlier part. This statement applies both to the records from the sitting-up position published in the previous work referred to above, and to those from the lying-down position published in the present work.

With minor variations according to the type of restriction, all forms of cessa-

tion of breathing resulted in a constriction of the hand, and a rise of volume of the brain with larger pulse beginning the equivalent in time of two to three breaths after breathing is stopped, and reaching its height two to four breaths after breathing returns. Increased depth of breathing and artificial snoring tend to give a fall of volume of the brain with smaller pulse and larger breathing-wave in the volume, which condition remains throughout the period of special breathing.

There are very definite indications that the circulation change lags behind the mental process. This was shown in about twenty-five out of thirty tests; in the others the curve had reached or approached the waking condition before the subject signaled that he was awake.

In all this work I have spoken very little of the changes in the hand and foot. This is partly because fewer results were taken from these than from the brain; partly because movement more often obscured those that were taken; partly because no constant reaction was obtained. Sometimes the hand increased as the individual went to sleep, but usually fell nearly or quite to the waking condition again, before the brain had reached its height. Sometimes there was no significant reaction in the hand with going to sleep, and it might even be decreased. All stimuli and all awakenings caused a constriction of the hand, but these constrictions were in part, at least, only temporary. So far as any conclusion can be drawn, it is that there is no rule in regard to the volume of the periphery in sleep. It would be desirable to study this question carefully by means of the finger plethysmograph which records more accurately the local vaso-motor changes.

With oncoming of sleep, the most characteristic change in breathing is decrease in amplitude of the abdominal movements and relative increase in the chest, combined with the fact that the sleeper tends strongly to pull his head towards his body in inspiration and push it from his body in expiration During sleep there are three types of breathing, with various intermediate forms. First, a period of shallow, slow breathing, usually, but not always, with heavy snoring, alternating with a period of deeper, freer, and more rapid breathing, which begins abruptly; this alternation shows in both chest and abdomen Second, a regular breathing intermediate between the extremes of the first type, but with the chest (perhaps the total) movement deeper than in the previous waking condition, and with regular snoring which produces a sort of halt or plateau on the inspiratory part of the curve The artificial snoring spoken of above differed from this in that the resistance was there mainly at the beginning of inspiration. Third, deep, regular breathing without particular snoring. In nearly all curves of this type there was some evidence of a somewhat irregular alternation of periods of deeper with periods of shallower breathing, but no definite change in rate. While in the first type the period of deep breathing begins rather abruptly, in the third there is a gradual transition from one to the other. Sleep most often began with the first type, which then, in the majority of experiments, gave place to the second or third type.

Stimuli during the first two types gave an increased amplitude, usually with

faster, sometimes with slower rate, always with relative increase in the abdominal movements. Stimuli during the third type usually gave a period of shallower and faster movements, which with stronger stimuli was followed by a period of increase. Stimuli rarely gave no breathing change even with a quite marked reaction in the circulation record. Awakening began with the same effects as stimuli; and as the subject became thoroughly awake, the abdominal movements became greater, the chest less than during sleep, with the rate sometimes decreased, more often increased.

There is a very prominent breathing wave in the curves from the hand and brain during sleep, particularly in that from the brain. It is diminished with reactions to stimuli and at awakening. This wave is greater with snoring than without. With snoring it is much greater than that with artificial snoring when awake. Without snoring it is often greater than similar deep breathing awake. These statements are particularly true when the first form of brain plethysmograph is used.

There is an undulation in both brain and hand curves covering several breaths, which we shall call the Traube-Hering wave, although possibly it should be called the Mayer wave. This gives place to a wave which is usually larger and longer during sleep, whether with a change from passive to active or not, only the blood-pressure measurements which we shall study later can make sure. As a rule, these waves nearly correspond in the brain and hand curves, they differ from each other by no more than two or three pulse-beats; but they often differ widely in relative size, and at times, particularly when the subject is going to sleep, some of the waves may be at nearly opposite phases in the two records. During sleep, any periodic fluctuation of breathing is to be correlated with the wave in the circulatory record. The deeper breathing corresponds to a fall and trough of volume, the more shallow to a rise and crest. In the abrupt transition from restricted to freer breathing of the first type, the change to deep breathing is very nearly simultaneous with the beginning of the fall of volume, most often a couple of pulse-beats before it, sometimes even as much after it.

CHAPTER III

THE BLOOD PRESSURE

Method

At first an attempt was made to use the Mosso sphygmomanometer to measure the variations of blood-pressure during sleep. The result was a failure. It is impossible to estimate the blood-pressure by compression of vessels that may actively relax or constrict from test to test. Furthermore, the instrument and position are altogether too uncomfortable for work on sleep.

The apparatus finally used was as follows. A sleeve (Riva-Rocci or Erlanger) was fastened around the left arm above the elbow. The Riva-Rocci sleeve was used in the first experiments, the Erlanger in the later ones. The mercury manometer was placed on the table in the operator's room, and connected to the sleeve by a thick-walled rubber tube. A light weight plethysmographic bulb was then bandaged firmly on the left wrist over the radial artery and connected to a medium piston recorder. In some cases a medium weight bulb was also bandaged on the flexion side of the lower arm just below the elbow, and connected to a second recorder.

To prevent bending of the wrist from interfering with the bulbs, a thin board was laid along the back of the hand and arm, and straps fastened to the board were buckled lightly around the hand and arm.

In order to make use of the criteria of Erlanger, the apparatus was further complicated in the later experiments. A shallow cup with outlet to the side was covered with several thicknesses of rubber-dam, and then fastened firmly to the operator's table. A three-way glass tube was inserted into the rubber tube between the manometer and the sleeve. The third branch of this was connected by a rubber tube to the outlet of the cup. Consequently, when the pressure was raised in the manometer system, the rubber covering the cup was bulged out into an oval shape and showed all variations, including the pulse, in the sleeve. A second shallow cup was covered with a single layer of rubber-dam. A rod projected from the bottom of this cup and passed through a hole which was cut in a second rod and provided with a set screw. When this second rod was clamped above the first cup, therefore, the second cup could be moved downward until the two rubber coverings fit firmly together and any change in the one would cause a corresponding change in the other. The cavity of the second cup was then connected to a piston-recorder, which consequently recorded all changes of pressure, including the pulse, in the manometer system. The breathing and the brain volume were always recorded along with the blood-pressure tracings. The first form of brain plethysmograph was used in all cases for the brain volume.

It was found that movements of the subject, especially the breathing movements, almost invariably caused a slight movement of the arm, and this gave a fluctuation in the curve from the wrist or lower arm. To avoid this, a swing was suspended from the ceiling by a single strand, like that used in the work on the brain volume. When this was hung about an inch above the bed, and the subject's arm was placed in it, practically all effects of movement except the contractions of the arm muscles themselves were eliminated.

Before the apparatus for the study of blood pressure was completed, the first subject moved out of town. All the results of this kind were then obtained from the second subject, except a few special records which were taken from other normal subjects.

Results

I can best show the nature of the work by describing a few typical records. The kymograph was rotated rapidly, so that the length of paper occupied by each test was usually several feet. On this account it will be necessary to reduce the tracings considerably in the reproduction. Unless otherwise stated, the diameter will be multiplied by one-half.

July 27, III, no. 1 (Fig. 43, Plate 40) *and no. 2* (Fig. 44, Plate 41).—These are extracts from a very long record. A few inches in the beginning and a portion in the middle are omitted, since they show no additional point. The curves from the top down are the abdominal breathing, the chest breathing, the indicator line, a curve from the lower arm, the brain volume, and the tracing from the sleeve. The Erlanger sleeve was used. The signals on the indicator line were made by the operator, and the adjacent numbers show the pressure at that instant. The air had been pumped into the manometer system just before no. 1 began. The subject had been asleep and the oncoming of the pressure had disturbed but had not awakened him. It will be seen that throughout no. 1 and the first part of no. 2, the tracing from the lower arm fell gradually with a slight breathing-wave in it, and had to be raised artificially at times. All abrupt rises and falls in this, and abrupt rises in the curve from the sleeve are artificial. At *a*, the air was allowed to escape rapidly for a moment, resulting in a quick fall in the sleeve curve. At *c*, the escape was opened somewhat more. It will be observed that the fall in the tracing from the lower arm is not influenced by the irregularities in the sleeve record. At *b, d, e, f, g, h, i, j, k, l, m, n,* and some other places, the drums were stopped and lines of reference were struck in all records. At *o*, the fall in the brain volume was accompanied by a rise in the curve from the lower arm with some evidence of pulse, and the arm curve was dropped artificially. At *p*, the brain volume reached another crest, and the curve from the arm forms an arch which spans the trough in the brain record. The fall in brain volume after *p* was accompanied by another rise in the arm tracing with some pulse. At *q*, there was a slight secondary crest in the brain and a similar trough in the arm. The arm volume continued to increase, so that *p*, at which the pressure was about 110 mm., was the beginning of a permanent rise and the returning pulse. At

several other places, notably *r, s,* and *t,* a fall in the brain was accompanied by a relatively rapid rise in the arm curve, with larger pulse during the rise in the arm. The rise in the arm may begin one or two pulse-beats before the fall in the brain. The more rapid the rise, the larger the pulse in the arm. It will be seen that the pulse in the arm is regularly of the nature of a simple step-up in volume, and it is only just at the last of the record that the end of the pulse wave begins to fall below its crest.

Three forms of pulse with intermediate stages may be distinguished in the curve from the sleeve. In the first, the rise is sudden and the fall with small waves is gradual from the crest to the end of the pulse. In the second there is a greater rise and quick fall in the first part of the pulse-wave. The dicrotic and the latter part of the wave are relatively lower. The third is characterized by the more elevated dicrotic and normal pulse form. Towards the end of the record, it will be seen that, in spite of the slowly escaping air, the sleeve was actually lifted and held up by the returning blood, and the pressure increased from 103 mm. to 105 mm. The greater the returning pulse in the arm, the more the pulse form approached the third type; but the most definite appearance of the third type occurred at the time of elevation of the sleeve.

At several places a respiratory wave shows in the pressure curve. There are two very clearly just before *h.* The pulse is found mainly on the rise of the wave. This rise begins in the expiration and near the crest of the respiratory wave in the brain volume.

H., July 27, II (Fig. 45, Plate 42).—In the record described above, the paper was not long enough to show the last of the test fully. This extract is reproduced to illustrate the usual condition at the end. The subject was asleep except that the stimulus of the experiment disturbed him. The pressure had been on, and the arm volume had been sinking through three feet of record omitted at the beginning. The pulse from the sleeve had changed from the first type to an imperfect second type. At *a,* a short fall in the brain was accompanied by a slight rise in the arm curve. From 112 mm. to 101 mm. the pressure was allowed to fall rapidly. The arm curve began to rise with small pulse at about 111 mm. The returning blood lifted the sleeve and raised the pressure to 102 mm. The pressure was abruptly dropped to 98.5 mm. but the elevation of the sleeve again raised it to 100 mm. or more. The rise with pulse in the arm can be seen to be greater with falling brain volume and less with rising brain volume. Each pulse from the arm is a simple step-up in the curve until near the end, after the sleeve has been lifted considerably, when the end of the wave drops below the crest and the pulse assumes the usual form. The rise in the arm volume ceases at the same place. The pulse from the sleeve becomes of the third type with elevation of the sleeve.

The last portion of this record is especially typical. There is a slight breathing wave in the arm record before pulse returns. Its relations are uncertain. But the rise seems to begin on or just before the trough of volume.

June 23, I (Fig. 46, Plate 43).—The middle portion of this record is repro-

duced in order to show more completely the variations in the pressure curve that are often found before the permanent rise with the pulse begins. The curves from the top down are the chest breathing, the indicator line, the bulb on the wrist, and the brain volume. The pressure had been on and the wrist tracing had been sinking through two feet of record. The subject was asleep, at least lightly. At *a, b, c, d,* and *e,* the drums were stopped and lines of reference were struck. The brain volume showed a disturbance, a fall with smaller pulse at several places. A fall in the brain volume was accompanied by a rise in the curve from the wrist; a trough in the brain record corresponded to a crest in the record from the wrist. The amount of change in the two is fairly proportional. The change in the wrist curve may begin one or two pulse-beats before the change in the brain. The permanent rise with pulse began at about 115 mm. The more rapid the rise the greater the pulse, and a more rapid rise corresponds in general to a fall in the brain. In the latter part of the record, which is not reproduced, the rise in the arm continued until the pulse assumed its full form as in the above descriptions. It should be emphasized that fluctuations in the pressure curve corresponding to changes in the brain occur before a pulse has shown itself in the pressure curve. In this respect this record is typical of many others.

The rise in the small respiratory wave in the wrist tracing begins during the rise of brain volume, sometimes near its crest.

May 4, III, Test 1 (Fig. 47, Plate 43).—The diameter was multiplied by three-fourths. The pressure had been on only a short time when this extract began. The subect was sleeping lightly. The curves in order from the top are the abdominal breathing, the chest breathing, the indicator line, the brain volume, and the wrist (radial). At *a,* the subject was disturbed, the abdominal breathing increased and there was some movement. The brain volume fell with smaller pulse. The curve from the wrist rose with some evidence of pulse. This reaction was followed by a period of restricted breathing and rising brain volume, the wrist curve turned downward and the pulse disappeared from it. The permanent rise began at about 145 mm., although there is little evidence of pulse until 143.5 mm. At *b,* lines of reference were struck. Just afterward there was another disturbance with increased abdominal breathing and falling brain volume. At the same time the curve from the wrist showed a great acceleration in its rise. Then followed a period of restricted breathing, rising brain volume and slower rise in the wrist. After the portion reproduced, the rise in the arm continued until the return of the fully formed pulse. The Riva-Rocci sleeve was used in this test and in all others that show similarly high readings with this subject. It will be seen that there is a small breathing wave in the wrist tracing. Measurement shows that the rise in this begins just before the crest of the breathing wave in the brain volume and in the beginning of expiration. A quick pulse followed by a delayed one obscures the form of the curve in several places.

May 16, I (Fig. 48, Plate 44).—The pressure had been on and the wrist curve had been sinking with shallow waves through three feet of record when this extract began. Periods of sleep with restricted breathing and some snoring

alternated with periods of deeper, freer breathing. As usual the restricted breathing was accompanied by a rising brain volume, the freer breathing by a falling brain volume. Corresponding to the fall in the brain, there was a rapid rise in the tracing from the wrist with marked pulse. Corresponding to the rising brain volume, there was a slower rise in the wrist curve, or none at all, with little or no pulse. There were four periods of this kind during the extract. Under these circumstances it is difficult to place exactly the beginning of the permanent rise which represents the average blood pressure at the moment. It was counted at 127 + mm. Lines of reference were struck at the end. Measurements from these showed that each accelerated rise in the wrist curve began a little before the fall in the brain, and the increase in breathing began, if anything, before the rise in the wrist.

May 16, II (Fig. 49, Plate 43).—The wrist curve had been sinking through about two feet of record. This extract also shows an alternation of restricted breathing and rising brain volume with increased, freer breathing and falling brain volume. But there were in addition several shorter waves in the brain without corresponding definite breathing changes. The fall in brain volume again accompanies a rise in pressure. Lines of reference were struck at *a* and *b*. In reproducing, the engraver painted out the reference line under *a*, in the pressure curve. In attempting to restore it, he placed it too far forward and deformed the curve somewhat. Measuring from these it is found that the rise in pressure began a little before the fall in brain volume in two cases, a little afterward in two cases and nearly simultaneously in the other cases. The breathing change just after *a* was slightly delayed, the others began a little before the change in pressure. In few records was it as difficult as in this one to determine an average point of permanent rise. It was taken as 151.5 mm. A few inches after the close of the portion reproduced the subject entirely awakened with considerable movement, and the full pulse form soon returned.

May 30, I (Fig. 50, Plate 45).—The brain curve is imperfect in this record because of trouble with the recorder; but it is still adequate to show the changes of volume. The subject was asleep. This extract is reproduced to illustrate more completely the effect of disturbance followed by return to sleep. The brain tracing had been raised artificially and a slight rise in the pressure curve had begun while the subject was still snoring. At *a* the snoring ceased and the subject was much disturbed. The brain curve fell and had to be raised. The wrist (radial) curve rose rapidly with pulse. Then the subject began to rest again, the brain volume rose, the pressure curve lost its pulse wave, rose more slowly, and then fell. Just before *c* another rise in the pressure tracing with falling brain volume began. The permanent rise was taken as 111 mm., which was still 5.5 mm. less than the records taken while awake the same night. Lines of reference were struck at *b* and *c*.

There is a respiratory wave in the wrist curve. The rise begins in the expiration.

May 3, II (Fig. 51, Plate 46).—This is a short extract which is reproduced in

order to show better how the breathing wave may influence the pulse in the pressure curve. Each wave usually begins with a small pulse followed by one or two larger ones on the rise, while on the fall, the pulse is absent or much smaller. Measurement from lines of reference at the end of the test (not reproduced) showed that the rise with pulse in the pressure record begins on the rise of the breathing wave in the brain. A slip of the paper at *x* serves as an approximate reference line. The pressure wave is at least a pulse-beat later than the corresponding wave in the brain. The subject was asleep. The diameter was multiplied by three-fourths.

May 4, I. Test 2 (Fig. 52, Plate 47).—The subject was nearly awake. The tracings from the top down are abdominal breathing, chest breathing, indicator line, brain volume, and curve (pressure) from the wrist. The pressure had been thrown on while the drum was stopped at *a*. This disturbed the subject. At *b*, occurred a period of restricted breathing and rising brain volume accompanied by a falling pressure curve with no pulse. At *c*, began increased breathing, falling brain volume and rising pressure tracing with pulse. This was the permanent rise, which therefore began at 146 mm. There is a considerable respiratory wave in both brain and pressure curves. There is a noticeable pulse on the rise of the pressure tracing, little or none on the fall. The rise of pressure begins near the crest of the volume wave during expiration. The crest of pressure occurs not far from the trough of volume, during inspiration. A given phase of pressure occurs rather before than after the opposite phase of volume.

The extract is reproduced in the original size.

July 27, VI (Fig. 53, Plate 48).—This is reproduced for comparison with July 27, II (Fig. 45, Plate 42) and III (Figs. 43 and 44, Plates 40 and 41). It is an extract showing the beginning of the permanent rise and pulse. The brain plethysmograph was adjusted to show a better pulse. The subject was awake but drowsy. At *a, b, d,* and *e,* lines of reference were struck by stopping the drum a moment. There are several artificial changes in the pressure and sleeve curves. At *c*, the tracings were somewhat confused by movements of the subject. The permanent rise with some pulse began about 118 mm. and became more definite at 115.5 mm. At several places, notably following *d* and *e*, a fall in the brain volume was accompanied by a rise, or more rapid rise, in the pressure curve, with emphasized pulse. The effect in the pressure may precede the brain reaction one or two pulse-beats. A higher position of the dicrotic in the sleeve curve answers to an increase in the pressure tracing, but the change in the sleeve curve cannot be determined with so much certainty.

July 13, III (Fig. 54, Plate 49).—The subject was awake, but very drowsy. The curves from the top down are the abdominal breathing, chest breathing, indicator line, wrist, brain volume, and lower arm. Lines of reference were struck at *a, c, d,* and *e*. The pressure was not on at first, and it will be seen that the undulations in the curve from the wrist were very nearly parallel with those in the brain volume. The curve from the lower arm follows a similar course, but the correspondence is not always so exact. In such respects this record is

especially typical. At *b,* the pressure was thrown on. Following this, the brain volume showed several undulations of different lengths. In each case the rise in the pressure curve corresponds to a fall of brain volume, the pressure curve forms an arch answering to a trough in the brain record. The change in the pressure record may be delayed slightly, not more than a pulse-beat. The tracing from the lower arm changes in the same direction as that from the wrist, but the reaction is always the larger in the lower arm. In large changes like that at *f,* it is of course necessary to reduce to the recorder level, in order to determine the phasic relation.

The last part of this record was run alternately slowly and rapidly in order to study pulse form, and is, on that account, not reproduced here.

B., June 21 (Fig. 55, Plate 50).—The diameter is multiplied by three-fourths. Several blood pressure records were taken from other subjects while awake, in order to study the technique of the method, the relations of the Traube-Hering wave, and other matters. This is an extract out of a record from a strongly built man B., whose blood pressure was about 30 mm. higher than that of the second trephined subject. Since it was of course impossible to obtain a brain tracing, a curve was taken from the right hand, while the left arm was used with the blood pressure apparatus.

The blood had begun to return at 145 mm. and the present extract represents the condition after 5 mm. more of fall. The curves from the top down are the chest breathing, the indicator line, the wrist tracing and the plethysmographic curve from the right hand. Lines of reference were struck at *a* and *b*. Measurement shows that the undulations in the pressure record parallel almost exactly those in the hand volume. A rise with pulse in the pressure corresponds to a rise of hand volume, a fall of pressure corresponds to a fall of volume. The largest pulse in the pressure tracing is always at the crest of the wave, or on the rise and crest. This extract is typical of all tests with the subject *B*.

W., July 11 (Fig. 56, Plate 50).—This extract is reproduced full size. It is from another subject *W*. It was taken to show the effect of sudden changes of pressure in the sleeve. The curves from the top down are the chest breathing, the indicator line, the volume of the lower arm, the volume of the wrist, and the sleeve record. The question was whether the gradual fall which is always found after the pressure is thrown on, could be in any way influenced by or due to change of pressure in the sleeve. A breathing wave shows in the arm curve, very slightly in the wrist. At the mark, the pressure was suddenly raised in the manometer system by pressing the inflator, and, after a few pulse-beats, was as suddenly released. There was no noticeable effect upon the wrist or arm curves; both continued their descent without interruption.

Summary

The net result of the study of blood pressure is as follows. After the pressure is thrown on, there is a gradual fall in the volume of the wrist and the lower

arm, and, I may add, three curves taken from the hand showed the same result. There is, then, a general decrease in volume which signifies an escape of blood from the member below the sleeve. This decrease cannot be due to the release of pressure in the sleeve, since it is not influenced by a rise or fall amounting to several millimeters in that pressure. Even before the pressure in the sleeve has fallen to the point at which a pulse returns in the occluded portion, a wave may be found in the pressure tracing which checks the fall or causes a rise in the tracing. Records taken simultaneously from the wrist and lower arm or wrist and hand show that this wave is parallel throughout the occluded portion and therefore cannot originate within that portion. Waves from the wrist and lower arm are more absolutely parallel to each other than before the pressure was applied. But all reactions are more emphasized in the lower arm than in the wrist. Furthermore the wave is too regular to be in any way probably due to movement. We may infer that it is caused by a wave in the general blood-pressure and that blood is getting through below the sleeve. This blood-pressure wave is related to the wave (Traube-Hering) in the volume record (brain or other hand) taken at the same time.

When the fall in the sleeve pressure has reached a certain point, a rise shows itself in the curve from the occluded portion, and at the same time or soon afterwards, a pulse begins in the same curve. Both may be visible in the lower arm somewhat before they are in the wrist. The appearance of pulse never delayed more than three millimeters after the beginning of the rise, and the two were more often practically simultaneous. When there were fluctuations, as was usually the case, the pulse was present or emphasized on the rise of the wave and tended to disappear on the fall. This wave corresponds to the earlier wave in the pressure tracing except that, measured by its phasic relation to the simultaneous volume changes, it seems to show itself a little more quickly, perhaps as much as two pulse-beats. Such a relation to pulse makes certain the conclusion that the fluctuation is due to blood pressure changes. Furthermore, the phasic relation of the wave in the curve from the occluded portion to that in the volume of brain or hand is the same with all variations in length of wave. This shows that there is no appreciable delay in the expression of the blood pressure change in the tracing.

After an additional fall of three to ten millimeters (the average was six and one-half millimeters) in the sleeve pressure, the sleeve curve began to rise and the pressure in it was increased one to three millimeters. This was without doubt due to elevation of the sleeve by the returning blood. The exact point at which it occurred, seemed to depend not merely on the amount of fall in pressure but also upon the time allowed for blood to accumulate in the portion below the sleeve. In some cases, disturbance of the subject by the returning circulation hastened it. But the elevation did not show itself until enough blood had accumulated in the occluded portion to sustain the sleeve. Such an elevation might be of some importance in a method of "staircase-curves."

With the lifting of the sleeve, the rise of volume in the occluded portion

became less and soon ceased. The pulse from the wrist and lower arm was, during the rise in these curves, a simple step-up in volume. As the sleeve rose, and the volume of the occluded portion stopped its rise, this pulse assumed a more normal form. Three forms of pulse were found in the sleeve curve. There was increase in size and elevation of the dicrotic in the sleeve pulse with the returning blood, especially with the lifting of the sleeve.

Using the rise in volume of the occluded portion, especially when accompanied by pulse, as the criterion of pressure, the records show the following facts. The blood pressure was several millimeters lower during sleep than during the waking condition. The difference was usually 8 to 10 mm. But the series (July 27) which seemed most satisfactory from every standpoint at the time gave only 5 mm. On the other hand, one series showed a difference of 17 mm. I will quote six series in which the subject slept well enough to make a fairly accurate and continuous series possible. Each test is enclosed in parentheses; and in each, the condition of the subject, the point of permanent rise, and the point of returning pulse are stated in order, with dashes between. The tests in each series are given in the order in which they were taken. But, since two tests were sometimes taken on a single paper, the number of the test does not always correspond to the number of the paper, which was used for reference with those reproduced above. Series April 27 was (awake—151.5—151.5), (asleep—144—144), (asleep until blood returned—141.5—141.5) and (awake—152—152). Series May 3 was (nearly asleep—134—131), (asleep—131—128), (disturbed and moving—136—136), (nearly or quite asleep—126—125) and (awake—134.5—134.5). Series May 4 was (awake—148.5—148.5), (waked as test began—146—146), (asleep—139—136.5), (asleep—138—136), (waked in test—145—143.5), (waked in test—143—142), (asleep—139—139) and (awake but drowsy—143—141). Series May 30 was (partly asleep—111—111), (more deeply asleep—110—107) and (awake—116.5—116.5). Series July 6 was (sleeping lightly, awakened in test—117—114), (light sleep—115—112), (awakened as test began—120—120), (asleep—107—107), (wakened and began to move in test—124.5—124.5) and (awake—124—124). Series July 27 was (asleep—113—110), (asleep—111—111), (asleep—110—110), (asleep—113—110), (lightly asleep—113—110), (awake—118—115) and (awake—115—115). I am unable to trace any definite curve of sleep in the pressure, perhaps because of the irregular disturbance of the subject.

With the second subject it is found that the Traube-Hering wave in the brain volume is an active process, both while the subject is asleep and while he is awake. The fall of volume occurs during the rise of pressure, the rise of volume occurs during the fall of pressure. In the majority of cases the rise of pressure begins one or two pulse-beats before the fall of volume. Sometimes it is slightly delayed. Since the wave in the undisturbed hand is approximately parallel to that in the brain, it is also an active process. With the subject B. the Traube-Hering wave, in the hand at least, is found to be a passive process. The volume rose with rising pressure and fell with falling pressure. With the subject W. the wave in the hand is a mixture, sometimes primarily active, sometimes primarily passive.

It is, of course, impossible to say with certainty whether these statements would hold of the brain if a record could be taken.

Disturbance during sleep invariably caused a rise of pressure with falling brain volume. The rise of pressure sometimes showed itself one or two pulse-beats before the fall of brain volume. Less often it was slightly delayed. Return to sleep, or even drowsing, was always accompanied by a falling pressure and a rising brain volume.

A respiratory wave is found in many of the records. The relations are of course most certain after the pulse has begun to return. There is then no possibility of error, such as there is when the pressure in the sleeve is very high, from a delay in the actual change in pressure showing itself in the curve. The fact that the pulse-beats vary in length, especially when an unusually short beat is followed by an unusually long one, enables one to identify the same beat in different curves, and to compare their temporal positions. It is found that there is no important delay on account of the sleeve. And since the pressure change shows itself in the change in size of pulse breaking through, as well as in the change in level of the pressure curve, we may infer that there is no appreciable delay in the change in pressure showing itself in the pressure curve. The rise with pulse in the pressure curve begins on the rise of the respiratory wave in the brain volume, the fall of pressure begins on the fall of volume. Most often the relation is such that the rise of pressure begins just before or even sometimes on the crest of volume. This is true with slow breathing and long waves, where delay would play less part, as well as with more rapid breathing and shorter waves. I am not sure whether there is a difference between sleeping and waking; but, if anything, the rise of pressure seems to begin earlier on the rise of volume during sleep.

Study of the change in size of pulse and position of the dicrotic in the sleeve curve confirms the conclusions from the wrist and lower arm curves. But in my own records at least, I can be more certain of the changes in the wrist and lower arm than of those in the sleeve curve.

While waiting for the subject to go to sleep, the kymograph was often run slowly as in the study of volume changes. The results, therefore, constitute additional evidence of the changes in brain volume with the second subject lying down and using the first form of brain plethysmograph. Altogether there were eight unambiguous cases of going to sleep, all of which gave a rise of volume with larger pulse. There were ten cases of awakening, all of which caused a fall of brain volume with smaller pulse.

CHAPTER IV

THE HEART RATE AND PULSE TRANSMISSION TIME

Method

The heart rate is so obviously a possible factor in the circulation changes which accompany sleep, that it is necessary to determine it accurately. A study of the transmission time within the arteries was added for a different reason. All methods of blood-pressure measurement, such as the process described in the previous chapter, are subject to one criticism. They act as a stimulus to the subject, especially when applied to a sleeping individual. Since the rate of transmission of the pulse wave is supposedly influenced primarily by the tonicity of the vessels and by the blood pressure, it was thought possible to obtain by this means some indication of changes in sleeping and waking, and with reactions during sleep. The exact pressure could not be given of course, but the direction of change might be ascertained; and the taking of the record does not act as a special stimulus to the subject.

To measure both the heart rate and pulse transmission time, I recorded the chest breathing, the abdominal breathing, the brain pulse, the carotid, the femoral and the tibial. The subject lay on his back in all tests. The first form of brain plethysmograph was used for most of the work, the second form for a part, however. To obtain the carotid pulse, a funnel-shaped cup was covered with rubber of medium thinness, and a square piece of cork about four millimeters thick was attached to the rubber by means of beeswax. The cup was inverted on the throat, and the cork placed over the carotid. Straps attached to the sides of the cup near its smaller end were then fastened firmly around the neck, and a tube was led from the smaller end of the cup to a piston recorder.

The femoral was recorded as follows: A strip of heavy card-board two inches wide was bandaged to the outside of the right leg. It extended up past the hip. A shallow tambour cup covered with medium weight rubber and a piece of cork four millimeters thick and one centimeter in diameter was attached to the center of the rubber covering. The cup was inverted and the cork placed upon the femoral. A broad bandage was passed around the thigh, over the cup and through a slit in the upper end of the cardboard, and was pinned or tied firmly. A tube led from the cavity of the cup to a piston recorder. The cardboard was of course necessary to prevent the bandage slipping down, and was better than a belt around the waist since it was not influenced by respiratory movements.

For the tibial curve an elliptical rubber bulb having a moderately heavy wall was placed over the artery, and a bandage passed firmly over it and around the ankle. The bulb was also connected to a piston recorder.

The recording points were arranged as nearly as possible along a plumb line. An arc was struck with each to serve as a line of reference. Similar arcs were also struck at the end of each record. On the first record of each night's work, the recording needles were set level and the kymograph was run a few centimeters. This gave the position of the level line of each recorder. The order from the top down was the abdominal breathing, the chest breathing, the indicator line, the time line, the femoral, the brain, the carotid and the tibial. The time curve was given by an electric marker. This was driven by a current which was interrupted by a tuning fork at the rate of fifty times per second. The kymograph was run rapidly enough that the intervals desired could easily be measured in two-hundredths of a second, and with some accuracy in one-thousandths of a second. A long paper would usually ascend about five millimeters on the kymograph in going around once. Such a rise did not cause a measurable error, but made it possible to rotate twice without stopping, and yet not obscure the record. This was often necessary in order to include a period long enough for a reaction to take place.

After the apparatus was adjusted, one or two records were taken while the subject was still awake. He was then allowed to go to sleep, and as many records as possible were taken before he awakened. In a part of these the subject slept deeply and evenly; in a part the assistant gave a stimulus which disturbed but did not awaken the subject; and a part were taken when periods of restricted breathing alternated with deeper, freer breathing and each record was timed so as to include the change of breathing. After the subject awakened another record was taken.

After every record the assistant reported the condition of the subject during the test, and after awakening, the subject was asked for any introspections.

The evaluation of the records of these tests was the most difficult task in the entire investigation. In the first place, the reports of the assistant and the subject's introspections were examined, and all records in which the condition of the subject was doubtful were thrown out. Also those were thrown out in which movement of the subject, breaking or leaking of any of the apparatus, or other accidental circumstance had so obscured the curves as to make an accurate evaluation impossible. However, a few were retained in which either the tibial or femoral curves were too uncertain to be used. Those of value were worked up as follows.

At the instrument shops of the University, three circles of tin were cut, one with a radius of 8.7 cm., one with a radius of 10 cm., and one with a radius of 12.3 cm. It will be remembered that these were the lengths of the writing levers of the different recorders used. A small hole was drilled in the center of each circle. Then a sector of approximately thirty degrees was cut from each circle, except that a small ring, 5 mm. in diameter, was left around the hole in the center.

The first step with each record was to draw the level lines for each curve; *i. e.*, the lines which the recording needle would have made if it had remained stationary in a level position. This involved only the drawing of lines parallel to the

indicator line and at the required distance from it. But it is important to get these accurate. A slight error in the position of the level line is, of course, of more importance when the curve is far from the line, than it is to not reduce to level when the curve is near the line; for the displacement is more in proportion the farther the needle departs from its level. Then the beginning of each pulse-beat was marked with a needle, and by use of a magnifying glass. This was the most uncertain part of the process. It is impossible to determine with finality the beginning of a pulse. In some tracings there is a definite bend in the curve where the main rise begins. In such cases this point was taken as the beginning. In other curves, the transition from one pulse to another was rounded and indefinite. In such cases a strip of celluloid on which parallel lines were ruled one millimeter apart, was placed so that one of the lines coincided with the level line of the recorder, and the lowest point of the curve was observed and marked as the beginning of the pulse. The femoral pulse was particularly troublesome. In some cases it seemed to be complicated by a slight movement somewhat like that of a venous pulse, of the real nature of which I am not certain. The instrument with which the pulse is taken certainly makes a difference in the time at which the rise will show itself. The first form of brain plethysmograph is obviously more analogous to the covered cup with which the carotid is taken than is the second form of brain plethysmograph. And we shall find that the results from the first form were much the more reasonable. Any pressure like the tension of the rubber of the covered instruments tends to delay and round the rise. Obviously, so far as the pulse is from small arteries, a condition of constriction of the vessels might interfere with the rise showing itself. In all results then, errors of unknown character are involved. If one's standard could be kept the same and the shape of the pulse did not change throughout a given set of records, the error would at least be reduced to a minimum. But such an ideal is never attained, and the irregularities due to uncertainties as to the beginning of the pulse very nearly rendered useless the exact methods I was able to employ in other respects.

The beginning of each pulse was then reduced to the level line and the corresponding position marked on the time record. To do this, a celluloid straight-edge was laid along the indicator line and held in position by weights. The sector whose radius is the length of the recording lever concerned, was placed so that one of its radii lay along the level line and its arc was in contact with a needle thrust through the beginning of the pulse. One side of a square was placed against the straight-edge and moved along it until the other side met the arc of the sector, which it should do at the intersection of the arc and the level line. This gave the position desired on the time line which was marked with a needle. Different lengths of marks were used for the different arteries, so that they could be easily distinguished. The time was then counted by use of a magnifying glass from each carotid mark to the next, for the length of the pulse; from the carotid to the brain, from the carotid to the femoral, and from the femoral to the tibial for the transmission times. Where the femoral could not be used, the count was made from the carotid to the tibial.

In all this process certain errors are involved which must be corrected. In the first place, it is generally impossible to arrange the recording points exactly in a line perpendicular to the indicator and level lines. To measure the error due to this, the straight-edge is placed along the indicator line. One side of the square is moved along it until the other side touches one of the arcs struck at the beginning by the needles, and a line is drawn along this side. A similar line is drawn for each of the arcs unless two or more of them fall on the same one. A check upon accuracy is that the vertical line should be tangent to the arc at the intersection of the level line. The distances between the vertical line of the carotid, and those of the brain and femoral, and the distance between the line of the femoral and that of the tibial are measured. Where the femoral is not used, the measurement is from the carotid to the tibial. These measurements give the corrections to be added to or subtracted from the positions of the pulse-beats. If the carotid vertical is in front of the brain or femoral, the correction is to be added to the latter, if the carotid is behind, the correction is subtracted. Likewise if the femoral is in front of the tibial, their difference is added; if the femoral is behind, the difference is subtracted. In practice, the differences were converted into terms of time by reference to the time record, and the results added to or subtracted from the transmission times. Where the kymograph ran regularly, only one evaluation of the differences in terms of time was required; but when the rate was irregular, of course several were necessary.

Furthermore, it was impossible to have all recorders in exactly the same plane, and, consequently, all needles did not move quite parallel with the plane of the paper. On this account, any great rise or fall in the curve caused an extra displacement of the writing-point forward or backward. The arc struck at the beginning is not a perfect circle; it was somewhat elliptical. To obtain the correction necessary at any given elevation of the curve, a pin is thrust through the arc at the beginning, at the given elevation, the corresponding sector is placed with one radius along the level line, and its own arc in contact with the pin. The length of level line intersected between the arc of the sector and the arc struck by the needle is the correction, the amount we must imagine the pulse to be moved backward. When of appreciable amount, this correction was always carried out.

Lastly, if on account of unevenness of the paper, a needle presses too hard at any place, this extra pressure will slightly straighten the curve near the end of the needle, and displace the writing point backward. If the heaviness of the line shows such an error to be active to a great degree, allowance must be made or the record thrown out. An indication of the correction may of course be obtained if the place is near the arcs struck at the beginning or the end.

After the record had been counted and the corrections made, the results were charted as follows. Coördinate paper was used on which the lines were ruled approximately six millimeters apart. For most of the records, four heavy horizontal lines were drawn to serve as standard lines. To plot the heart-rate, the standard line for the heart-rate was given the value of thirty-five, forty, fifty, fifty-five or sixty fiftieths of a second (represented as 35 P, 40 P, 50 P, 55 P, or

60 P at the left end of the line), and each unit of space above or below was given the value of one fiftieth of a second. Above is positive, below negative to the standard. Units of distance along it represent pulse-beats. Points were placed in the appropriate positions on the vertical lines to mark the length of each pulse. Thus if the standard is 50 P, a pulse of forty-eight fiftieths of a second in length will lie two spaces below the standard, one of fifty-three fiftieths of a second in length will lie three spaces above. A curve was then drawn through these points. A rise in the curve, therefore, means a slower heart-rate; a fall in the curve means a faster heart-rate.

To plot the transmission times, the method was similar. Times from the carotid to the femoral and from the femoral to the tibial were expressed in fiftieths of a second. These two were also added together, giving the time from the carotid to the tibial, which was also expressed in fiftieths of a second. It was plotted separately, since, being a longer time, it is less obscured by errors of marking and counting. The time from the carotid to the brain was expressed in two-hundredths of a second. The standard line for the carotid-femoral time was given the value of three, four or five fiftieths of a second (represented as 3 C. F., 4 C. F., or 5 C. F., at the left of the line), and each unit of space above or below was given the value of one-hundredth of a second. The standard line for the femoral-tibial time was given the value of three, four or five fiftieths of a second, and that for the carotid-tibial time was given the value of six, seven, eight or nine fiftieths of a second (represented as 3 F. T., 4 F. T., or 5 F. T., and 6 C. T., 7 C. T., 8 C. T., or 9 C. T., respectively). Spaces above and below had the value of one-hundredth of a second. The standard line for the carotid-brain time was given the value of zero, two, three or four two-hundredths of a second (represented as 0 C. B., 2 C. B., 3 C. B., or 4 C. B.), and each space above or below had the value of one four-hundredth of a second. The vertical line on which was represented the transmission times of a certain pulse wave, was also the line on which was represented the length of the preceding pulse wave.

To chart the brain volume, the distance of the beginning of each pulse beat from the level line of the recorder was measured, and marked as positive or negative. Then the same distances were laid off on the corresponding vertical lines of the coördinate paper, using the standard line in the place of the level line on the original record. A curve drawn through the points thus marked represents the volume changes in terms of the lowest points of the pulse-beats.

The chest breathing only was plotted. The level line of the tambour was drawn. The distance of the breathing curve above and below this line was measured in millimeters at a position corresponding to the beginning of each pulse, and at the crest and trough of each breath. The standard line on the coördinate paper was given the value zero, and each space above or below it the value of one millimeter. The measurements were then counted off on the corresponding vertical lines, and the points obtained connected with a curve. Thus the depth of inspiration is plotted below the standard line, the height of expiration above it.

Since the records were several minutes apart, and the brain tracing might be changed artificially between records, the position of the brain curve on one chart cannot be compared with that on another.

In most of the charts, the top standard line is used for the brain volume. The next is used for the carotid-tibial time, which is represented by a smooth line, and for the breathing, which is represented by a dotted line. On the third standard from the top are plotted the carotid-brain time, represented by a smooth line, and the femoral-tibial time, represented by a dotted line. The bottom line is standard for the heart-rate, drawn as a smooth curve, and the carotid-femoral time, drawn as a dotted curve. Where a different system was used, the arrangement will be explained in describing the individual record.

Lastly, it should be stated that all the records were first marked and counted and the necessary corrections calculated before any were charted. Each record was marked without reference to whether it was from waking or sleeping, a stimulus or even sleep, and without noting how the results were coming out. It was only after the charting was well advanced that I began to see what the conclusions would be. In this way I attempted to escape the influence of any previous theory or suggestion.

The second subject served for the main part of this work. One night's results were obtained from the first subject just before he left the city; but they included only the brain, carotid and femoral, and were not very satisfactory. The apparatus for the elimination of movement was not used. A few records for special purposes were taken from another subject Bi., using the carotid and radial.

Typical Results

I turn now to a description of several typical charts. The sides of the charts were multiplied by one-fourth in the reproduction.

H., May 20, VI (Fig. 57, Plate 51).—The subject was asleep. Periods of slightly restricted breathing were alternating with periods of somewhat freer breathing; neither period was extreme. This record, especially in the latter part, was a period of restriction. The chart shows the decreasing amplitude of breathing and the check in inspiration. The brain volume rose a little. The carotid-femoral curve shows no very certain change of level, but possibly a rise. The other transmission times are obviously increased. There is a very large respiratory wave in the heart-rate, and the average heart-rate was slowed somewhat during the record. The rate increases with inspiration and decreases with expiration, except that the change is somewhat delayed. The respiratory wave in the transmission time is of course most reliable in the carotid-tibial. The crest of the transmission time wave is usually on the rise or crest of the wave in the volume of the brain. The trough of the transmission wave tends to be somewhere on the fall from crest to trough of volume. The wave in the brain volume rises with inspiration and falls with expiration, except that the volume changes are delayed, especially the fall.

H., May 25, II (Fig. 58, Plate 51).—The subject was awake but drowsy.

The breathing was irregular, the third and the fifth breath much restricted. The first four brain pulses were obscured, their exact position doubtful. This portion is marked by a dotted line. The brain volume was low at first, rose in the center and fell again at the end. The transmission time was first rapid, then slowed, then accelerated again, and finally slowed a little toward the end. The slowing of transmission rate corresponds to a rise of brain volume, the acceleration to a fall of brain volume; but the change in volume is delayed a little behind the change in transmission time. The heart-rate curve fell with the rise in brain volume and transmission curves, and rose with the decrease of volume and more rapid transmission. It was apparently falling again with the slowing transmission. It shows a respiratory wave, but a comparatively small one.

H., May 25, VI (Fig. 59, Plate 51).—The subject was asleep. The breathing was restricted in the first part and became freer in the last part of the record. The brain volume was rising slightly at first, and fell toward the end with the freer breathing. The femoral was uncertain and only the carotid-tibial and carotid-brain times were measured. The transmission became more rapid towards the end with the fall of volume, the change in transmission beginning before the change in volume. The respiratory wave in transmission (carotid-tibial especially) is irregular and uncertain; but apparently the crest of the transmission curve comes on the trough or rise of the volume wave; the trough of transmission is somewhere on the fall of volume. The heart-rate shows a medium breathing wave. The rate became more rapid during the first period of rising volume, and slower at the end when the volume was low. And yet one cannot infer that the heart-rate change caused the volume change; firstly, because the rate was not much slower at the end than at the first of the record, although the volume was greatly decreased; secondly, because the pressure, indicated by the rapid transmission time, was higher at the period of low volume.

H., May 25, XI (Fig. 60, Plate 51).—The subject was awake but drowsy. This was a period of drowsing with slight restriction of breathing. There was some rise of brain volume. The femoral was obscure; only the carotid-tibial and carotid-brain were measured. The transmission curves rose, indicating fall of pressure. The respiratory waves in the transmission are irregular. The heart-rate shows a respiratory wave smaller than that in VI. The curve fell (faster heart-rate) while the volume and transmission curves rose.

H., June 8, III (Fig. 61, Plate 51).—The subject was asleep. At the cross the assistant touched him, he stopped snoring and breathed more freely. He began to breathe heavily again just after this record closed. The pulse-respiration ratio during the first part of the record was 4.25; that in the latter part was 4.6. One or two pulse-beats were obscured by a movement of the head, and omitted. A few others were omitted in some of the curves because exceptionally uncertain. The brain volume fell markedly following the stimulus. The brain was recorded by means of the second form of brain plethysmograph. As noted above in the description of method, this is not analogous to the covered cup used to record the carotid, and allows the rise of the pulse to show itself more quickly

than with the other instrument. The present curve illustrates the point. The standard line for the carotid-brain time has the value of zero, and the curve is sometimes even negative, an obvious impossibility.

With the first form of brain plethysmograph which was used in the preceding records, the times ranged around three or four two-hundredths of a second, a much more probable value. And yet, if each instrument is compared only with itself, the direction of change of the curve seems to be practically the same with both instruments. In this particular record I found it especially difficult and uncertain to mark the brain pulses.

The transmission time curves showed a tendency to rise during the first part of the record, and then fell after the stimulus. This fall lasted until the brain curve was well down its descent. The transmission curves then rose in the latter part while the brain continued to decrease. The heart-rate curve rose (slower rate) after the stimulus, and seems to have been responsible for the fall of pressure indicated by the slowing transmission time near the end. There is a considerable respiratory wave in the heart-rate; but the respiratory wave in the transmission time is uncertain and irregular in its relations.

H., June 8, IV (Fig. 62, Plate 52).—The subject was asleep. The assistant touched him at the cross, he stopped snoring and breathed more freely. The pulse-respiration ratio during the first part of the record was 4.25; that during the last part was 4.2. The femoral was too obscured to be used and only the carotid-tibial and carotid-brain were counted. The same remarks apply to the brain curve as in the preceding chart. The brain volume was rising a little before the stimulus, and fell fairly rapidly after the stimulus. The heart-rate increased before the stimulus, decreased afterward, and showed a slight tendency to increase again near the end. The carotid-tibial curve rose before the stimulus, fell and remained low until the brain had nearly completed its descent, then rose again at the end. The carotid-brain curve is not so reliable. It fell slightly, then began to rise when the stimulus came. Several pulses after the stimulus it fell markedly, and was just beginning to rise again at the end. The breathing wave in the heart-rate was large, that in the transmission times was irregular.

H., June 24, I (Fig. 63, Plate 52).—The subject was awake. The record is too short to be certain of the significance of changes. Apparently the brain volume shows a trough and the transmission times indicate a trough delayed compared with the volume. But the carotid-brain curve does not agree with this. The carotid-tibial time averages about 8.5 fiftieths of a second. The respiratory wave in the heart-rate is moderate. In this and all the following charts the first form of brain plethysmograph was used.

H., June 24, IV (Fig. 64, Plate 52).—The subject was asleep. The assistant touched him at the cross and disturbed him. The pulse-respiration ratio before the disturbance was 3.7, that after the disturbance was 3.25. The brain volume fell during the disturbance. The transmission time curves fell at the same time, the most consistent reaction being in the carotid-tibial. The heart-rate shows a large breathing wave and was slowed as a result of the stimulus. The crest of

the respiratory wave in the carotid-tibial, so far as it can be judged, falls somewhere on the rise of the wave in the brain volume. The other curves are irregular.

H., June 24, VII (Fig. 65, Plate 52).—The subject was asleep. A stimulus was given at the cross and resulted in a period of freer breathing. The pulse-respiration ratio before the stimulus was 3.5, that after the stimulus was 3.25. The stimulus caused a fall of brain volume. The heart rate at first showed a large respiratory wave. The effect of the stimulus was to give an average increase in heart-rate for a few pulse-beats, and then an extreme slowing with much reduced respiratory wave. The transmission time curves fell after the stimulus. This fall was partly recovered from before the end, probably as a result of the slower heart-beat, but the net result was a more rapid transmission with decreased brain volume. The crest of the breathing wave in the transmission time curves comes for the most part on the trough of volume. There is a low brain volume at the beginning without any apparent reason (perhaps the end of a preceding fall with break in breathing).

H., June 24, IX (Fig. 66, Plate 53).—The subject was asleep and a stimulus was given at the crosses. He moved and was considerably disturbed. The breathing became freer. The pulse-respiration ratio at the beginning was 3.5; at the end it was 3. The brain volume decreased markedly. The heart-rate was increasing before the stimulus. The effect of the stimulus was an extreme slowing. In the first part of the record the transmission time curves were falling along with the increasing heart-rate and slowly rising brain volume. The first effect of the stimulus was a still more rapid transmission time (higher pressure), but towards the end this was counteracted, apparently by the decreasing heart-rate. So far as it can be determined, the crest of the breathing wave in the transmission time corresponds to the trough of volume.

J., November 21, XIII (Fig. 67, Plate 53).—This is a chart of one of the records taken from the first subject. The smooth curve on the top standard line is the carotid-femoral time; the dotted curve is the breathing. The second standard line is that of the heart-rate. The bottom line is for the carotid-brain time.

The subject was asleep at the start. At the cross the assistant started to awaken him, and he was awake by the end of the record. In awakening, he moved, and the brain recorder was thrown entirely off the paper so that it had to be regulated artificially. This so obscured the volume change that I have not attempted to plot it. The breathing was irregularly disturbed, and finally became much shallower. The pulse-respiration ratio was 4.4 during sleep, and 3.7 in the latter part of the record during awakening. In the earlier part of the record, the heart-rate showed a large breathing wave and a prominent Traube-Hering wave. There is a suggestion that the increase in heart-rate in the Traube-Hering wave goes with the higher position of the transmission time curve (passive phase), the decrease in rate (rise of curve) goes with the lower position of the trans-

mission curve (active phase). With awakening, both respiratory and Traube-Hering waves were very much decreased in the heart-rate. The effect of awakening on the transmission curves was a definite fall (rise of blood pressure).

Bi., March 22, II (Fig. 68, Plate 53).—This is one of several records taken from the subject Bi. to test the effects of strong stimuli and of deep breathing upon the transmission time. The pulse tracings taken were the hand (by means of the rubber bulb) and the carotid. The hand volume is recorded along the top standard line. The smooth curve on the bottom standard line is the heart-rate, the dotted curve is the carotid-hand time. A loud whistle was blown between the crosses. It caused the subject to jump and frightened him. I have shown in a previous work[1] that very strong stimuli may have both an exciting and inhibiting effect upon the heart. The reaction is rarely so extreme as this, and it is impossible to say whether this case is due entirely to the strong stimulus or in part to the relief the subject felt after the whistle (which he knew would come). But I am reproducing this chart because such reactions in a smaller degree do often take place with strong stimuli when the subject does not expect the stimulus, is not under strain and does not feel relief afterward; also because it shows the effect of such heart-rate changes upon the transmission time. It will be seen that the heart-rate was increasing when the stimulus came, and decreased markedly afterward. The hand volume fell after the stimulus, then returned to normal. The transmission curve shows a sustained rise (lower pressure) soon after the stimulus, perhaps an effect of the decreased heart-rate. There is a noticeable Traube-Hering wave in the hand volume, somewhat obscured by the reaction, and a marked one in the heart-rate, especially in the first part of the record. There is also a suggestion of such a wave in the transmission curve. The trough of volume, on the whole, seems to correspond to the slower transmission (lower pressure) and the crest of volume to the faster transmission. Also the heart-rate seems to increase with the fall of volume and slower transmission and to decrease with the rise of volume as a rule. But these relations are not exact, perhaps on account of delayed effect.

Bi., April 2, I (Fig. 69, Plate 53).—This is another record from the same subject as the last one. The smooth curve is the heart-rate. The dotted curve is the carotid-hand time. The subject was breathing very long and deeply. The letters at the top indicate the positions of the crests and troughs of the respiratory waves in the hand volume. The waves in the transmission curve are in the same direction as those in the heart-rate, except slightly delayed. The crest of volume occurs at or just after the lowest point in the transmission wave (highest pressure), the trough of volume occurs at or just after the highest point in the transmission wave (lowest pressure). A part of the object in reproducing this chart is to show to what extent the method gives consistent and accurate results. Taken within a single record in this way, it seems reasonably satisfactory.

[1] "Organic Changes and Feeling," *American Journal of Psychology*, 1906, p. 553.

Summary

In general, when we consider merely the curves within a single record, the results are fairly consistent. A stimulus during sleep always causes a fall of brain volume and a faster transmission time (higher pressure) ; and almost always gives a slowed heart-rate, which may or may not be preceded by a brief acceleration, and which may later overcome the tendencies making for higher pressure. The pulse-respiration ratio may change either way with the slowed pulse. This slowed rate is certainly temporary, since it does not last until after awakening; but none of my records was long enough to measure its period. It is probably analogous to the fact that in waking condition a strong stimulus has both an exciting and inhibiting effect upon the heart, and often the inhibition is the more prominent. But in sleep, any stimulus that will particularly disturb the subject usually shows both effects, particularly the inhibitory. Awakening gave faster transmission (higher pressure) with the first subject. The results with stimuli are, then, consistent with the facts brought out in the blood-pressure tests. Whether the slowed heart-rate played any part there, with the other previous stimulus which the very test constitutes, I cannot say. Perhaps it helped in some of the more rapid recoveries of the blood-pressure curve after disturbances.

Only a few cases analogous to the Traube-Hering wave, or a part of it, were included in the records. Seven out of the eight cases seemed to agree with the conclusion in the blood-pressure tests with the subject H., that higher pressure (faster transmission) goes with falling volume, and lowering of pressure (slower transmission) goes with rising volume. With subject Bi., the indication was that the opposite relation holds. There is also some suggestion in nearly all records with all subjects, that the Traube-Hering increase in the heart-rate accompanies the passive phase (lower pressure), and the Traube-Hering decrease in heart-rate accompanies the active phase (higher pressure). This would be consistent with the result I obtained in the earlier work on Organic Changes if the waves in the hand there used were passive, which seems to be the more usual condition. But more work is necessary to be certain of the true relation. The breathing wave in the transmission time curves is often mixed up. Examination of all the charts shows that, as nearly as one can judge, the crest of the transmission wave occurs often on the trough, rise, or crest of volume, seldom on the fall; the trough of transmission curves occurs often on the crest (oftenest), fall or trough of volume, seldom on the rise. This is fairly consistent with the blood-pressure tests. But I think the indicated low pressure is more often at the trough of volume, the high pressure at the crest of volume in the present case than it was in the blood-pressure measurements. Possibly such is the case when the subject is more deeply asleep, as in the present case where the test does not constitute a stimulus. In the heart-rate curve, the respiratory wave is very much more prominent during sleep than during waking.

To compare the results as to heart-rate in waking and sleeping, I noted the general level of the heart-rate curve in each record belonging to a given night's work; then averaged those taken during sleep and those taken during waking

separately. The results are expressed as the length of a pulse in fiftieths of a second. With the first subject, the average of three charts of waking was 43; the average of seven charts of sleep was 44.5 (fiftieths of a second). With the second subject, the averages were as follows. May 20: three waking gave 56; three sleep gave 55. May 25: four waking gave 52; seven sleep gave 52. June 8: two waking gave 50.5; six sleep gave 49.3. June 24: two waking gave 49.5; six sleep gave 57.7. There was, therefore, no significant change except in one case where sleep gave a slower pulse. The most obvious change in the heart-rate is the large respiratory wave in sleep.

When we attempt to study the transmission times during sleep and waking, the results are less satisfactory. The records seem at first sight quite contradictory. It is not that the transmission time sometimes seems to increase and sometimes seems to decrease during sleep. But one curve may show one effect and others the exact opposite. The carotid-brain, the carotid-femoral, and the carotid-tibial may agree or disagree with each other. The fact seems to be that I was able to keep fairly successfully to a constant standard by which I judged the beginning of the pulse-beat in a particular curve of a given record. But I was unable to carry over the same standard from time to time and apply it to all records. Consequently with a given record, the results are regular; but a comparison of records brings out inconsistencies. Under these circumstances, only an average can have any real value. Obviously, the carotid-tibial times, since they are the longest, must be relatively least obscured by errors of method; and they are, in fact, least inconsistent. Averaging these times for sleeping and waking (the results being expressed in fiftieths of a second), we find that the records of May 20 give waking 8.37, sleep 8.66; those of May 25 give waking 8, sleep 8.8; those of June 8 give waking 7.5 (only one record usable), sleep 7.5 (on the basis of 6 records); those of June 24 give waking 8.37, sleep 8.9. Averaging the carotid-femoral times for the first subject gives waking 4.7, sleep 4.9. Averages of the other times with both subjects lead to similar results. Furthermore, the longest time during sleep is always longer than the longest during waking condition; and the shortest time during waking is generally shorter than any time during sleep. We may conclude then, that the transmission of the pulse wave is slower during sleep, and consequently the blood-pressure lower, when the subject is sleeping easily and the test is by a method that does not constitute a stimulus. This agrees with the results obtained by the methods used in the blood-pressure tests proper.

CHAPTER V

THE JUGULAR PULSE

The greater part of this investigation has been concerned with reactions in the arterial system. The object of the present section is to study to some extent the changes in the venous system which accompany sleep. Particularly, are there any appreciable alterations of pressure in the internal jugulars which could influence the curve from the brain? The second subject served for this work. The receiving cup used for the carotid pulse, but with the rubber dam under lower tension, was placed over the jugular and connected to the large piston recorder. The brain volume was recorded along with the venous pulse by use of either the first or second form of brain plethysmograph. The chest and abdominal breathing curves were taken as usual. It would seem that any congestion in the jugulars sufficient to cause a rise of brain volume would likewise raise the jugular curve. Especially, a venous pressure that can overcome the relatively high tension of the rubber in the first form of brain plethysmograph must of necessity distend the jugular and show itself by a rise in the tracing.

I will describe extracts from four records.

H., July 20, V (Fig. 70, Plate 54).—The curves, beginning at the top, are the abdominal breathing, the chest breathing, the indicator line, the jugular and the brain volume. The first form of brain plethysmograph was used. The first part of the extract is the end of a portion in which the drum was run rapidly. The definite venous pulse is obvious. The jugular apparatus had been put on only about five minutes before, and the air in the cup and tubes was probably still warming up. Hence the gradual rise in the curve. There is a prominent breathing wave in the jugular curve, which is undoubtedly in part due to movement in the chest wall and neighboring tissue of the throat. In fact, it is practically impossible to eliminate this error.

The subject was already partly asleep when the extract began. At *a, b, c, d,* and *e,* there are periods of increased breathing with accompanying fall of brain volume of greater or less extent. The brain curve was much more nearly the waking condition at the end than at the beginning. There were no corresponding definite changes in the jugular.

H., July 20, VIII (Fig. 71, Plate 55).—The jugular cup had been carefully readjusted and the strap slightly tightened to give a larger pulse, and, if possible, less disturbance by movement of the chest walls. The subject was sleeping lightly during this extract. From *a* to *b* the kymograph was run rapidly to show the pulse form. There are several Traube-Hering waves in the brain record. At times there is a suggestion of such a wave in the jugular. But the wave in the jugular is not parallel with that in the brain. Thus *c* marks a crest, and *d* a

trough in the venous curve. And *c* is just before a trough in the brain; *d* is slightly before a crest in the brain.

H., July 26, V (Fig. 72, Plate 56).—As in the above records, the brain curve is at the bottom and was taken with the first form of brain plethysmograph. The subject had been asleep but was beginning to be restless. This extract shows the largest reactions in the jugulars that I have obtained in any record. Periods of restricted breathing and rising brain volume alternated with periods of freer breathing and falling brain volume. An irregular heart-beat interferes with the evenness of the record. The brain curve a little after *b* is obscured by the fact that the needle was accidentally moved just as the fall was beginning. As a consequence, the piston had to be raised artificially. At *6*, the subject moved. The jugular curve shows marked reactions, but they are not parallel to those in the brain. At *a, 6,* and *c,* the fall of the brain tracing is accompanied by a distinct rise in the jugular. The return to normal was gradual. There was no sustained inspiratory position, so that these changes were probably not due to movement of the chest wall. Possibly the increased breathing activity, especially in the abdomen, caused an inrush of blood into the chest; and changed heart action may have played some part. In any case, the response in the venous system could not have been responsible for the reactions shown in the brain curve.

I shall not reproduce any of the records of going to sleep, since they were long and show no measurable change in the jugular.

H., July 17, IV (Fig. 73, Plate 56).—In all the records we have been describing, the subject was lying down on his back. This is an extract taken from an experiment in which the subject was sitting propped up. The second form of brain plethysmograph was used. The kymograph was running rapidly. The jugular cup was in the same position in which it had been used a few minutes before when a good venous pulse had been obtained with the subject lying down. The brain tracing is at the bottom. It will be seen that only an imperfect form of carotid pulse was given in place of the jugular.

The diameter of the record is reduced one-half in the reproduction.

This test was tried several times and with every possible position of the receiving cup. Nothing but an arterial pulse was ever found, except when the subject was lying down.

The study of the venous system has yielded mostly negative results. I will suggest that the Traube-Hering wave found may be an arterial wave from the neighboring tissues. In a few cases, it is more nearly parallel to the brain. On this account, as well as because of its relation to certain emotions, it is desirable that the circulation in the head and neck be more fully investigated.

CHAPTER VI

THE PULSE FORM

It is my purpose in this section to bring together several facts concerning changes in pulse form, mainly in the brain, which have revealed themselves in the various records. They will, I think, aid somewhat in the interpretation of the reactions in the brain, and also of the causes of pulse form in general. I shall first reproduce and describe a number of extracts from different records. Only a large enough portion will be given in each case to bring out the pulse form clearly.

J., December 1, I (Fig. 74, Plate 57).—This shows the pulse form from the brain of the first subject when he was lying down on his back. The dicrotic notch and wave are low. The primary wave is comparatively high, with steep rise and fall. This should be compared with the curves already described, from the first subject lying down. November 28, III (Fig. 35, Plate 33), shows about the highest dicrotic I have seen from the brain of the first subject under these conditions (awake lying down). In the records of waking reactions lying down, it will be seen that the dicrotic notch is often the lowest point in the wave. This is a very common occurrence. Furthermore, reactions to stimuli lying down very seldom caused a rise in the dicrotic. Practically the only cases that did this, show a rounded pulse like that always obtained by plugging the trephine.

On the other hand, examination of such curves as those from February 20 (Plates 2 to 7), especially IV, no. 1 (Plate 6), where the drum was running rapidly, shows that as the subject went to sleep, the dicrotic notch and wave were markedly raised in position. They were depressed again with awakening.

J., November 16, II, no. 1 and no. 2 (Fig. 74, Plate 57).—These are from the first subject sitting up nearly erect. In no. 1 he was awake, in no. 2 he had gone to sleep lightly. It will be seen that even when awake, the dicrotic is rather high in position. But when he goes to sleep, it is still more elevated, often to the level of the primary wave. The magnifying glass also shows in many cases a predicrotic wave.

J., December 19, III, no. 1 and no. 2 (Fig. 74, Plate 57).—These are from the first subject sitting propped up. In no. 1 he was awake. The dicrotic position is medium. After going to sleep, the pulse became so large that the kymograph had to be run rapidly in order to show the form. No. 2 is an extract containing two of the waves obtained in this way, immediately following a reference line. The dicrotic notch and wave are more prominent and much elevated in position.

Reference should be made also to the records reproduced above, especially February 6, II, no. 1 (Plate 19) and no. 2 (Plate 19) and January 30, III (Plate 18), and to those on waking reactions published in my previous work. A careful examination of all curves taken for reactions to stimuli while awake sitting up,

shows that the dicrotic was sometimes slightly lowered, sometimes slightly raised, but usually not definitely changed with the reactions.

H., November 10, IV, no. 1 and no. 2 (Fig. 74, Plate 57).—These are from the second subject using the first form of brain plethysmograph. He was drowsy but not asleep. In no. 1 he was lying down on his back. Immediately afterward he turned his head somewhat to the right, and no. 2 shows the condition then. The dicrotic was lowered in the position to the right.

H., November 10, I (Fig. 74, Plate 57).—The subject (second) was lying on his right side and was awake. The kymograph was run more rapidly. The first form of brain plethysmograph was used. The dicrotic was very low. But in most records taken under the same conditions, it is even lower. This shows about the highest dicrotic found in the second subject lying on his right side awake.

H., May 16, II, no. 1 and no. 2 (Fig. 74, Plate 57).—These are from the second subject awake using the first form of brain plethysmograph. He was lying down on his back. In no. 1 his head was turned a little to the right of the vertical, in no. 2 it was turned as much to the left. The pulse became larger and the dicrotic more prominent and more elevated.

H., May 3, I, no. 1 and no. 2 (Fig. 75, Plate 58).—The subject (second) was lying down on his back, and the first form of brain plethysmograph was used. In no. 1 he was awake, in no. 2 he was asleep. The pulse became larger with sleep, and the dicrotic notch and wave became much more prominent and elevated. There is a distinct predicrotic wave.

H., April 6, II, no. 3 and no. 4 (Fig. 75, Plate 58).—These are further extracts from the series of April 6, of which several have already been studied. All were taken from the second subject lying on his back and using the first form of brain plethysmograph. The kymograph was run rapidly to show pulse form. In no. 3 the subject was asleep; no. 4 was taken later in the same record when the subject had awakened. With awakening, the dicrotic became much depressed, but the dicrotic notch was not so low as when the subject was lying on his right side.

H., November 10, III, no. 1 and no. 2 (Fig. 75, Plate 58).—The subject (second) was lying down on his back with his head turned to the right, and using the first form of brain plethysmograph. In no. 1 he was awake, in no. 2 he had gone to sleep. When awake the dicrotic was extremely low and almost eliminated. With sleep the pulse became larger, the dicrotic notch and wave distinctly higher and more prominent.

H., February 16, I (Fig. 75, Plate 58).—The conditions were similar to those in November 10, III. The subject would go partly asleep with restricted breathing and rising brain volume and then awaken with freer breathing and falling brain volume. This extract begins with a period of disturbance and low volume, and ends with a period of light sleep and higher volume. The rise of volume is accompanied by a somewhat more elevated dicrotic. All such periods showed at least as much of a change as this, many of them more.

Examination of the pulse form in the records from the second subject which

are reproduced in the preceding chapters, agrees in every way with the changes found here. The dicrotic is depressed when the head is turned to the right, relatively elevated when the head is lying on its back. Sleep in any position gives a higher and more prominent dicrotic than the waking condition in the same position. When the second form of brain plethysmograph was used, the pulse form was sometimes modified by approach to an upper limiting line. Such a restriction will always tend to reduce all waves to the same level and give a more blunted or rounded pulse. But such curves as H., January 25, II (Plate 16), show that there is a lower dicrotic with waking conditions where there is no question of interference by a limiting line.

H., July 21, nos. 2, 4, 5, 7, 8 (Fig. 76, Plate 59) *and 11* (Fig. 77, Plate 60).—This series of records was taken from the second subject in midday and while he was thoroughly awake. The second form of brain plethysmograph was put on and the subject lay down on his back. His legs rested on the bed, and his body and head rested on a wide board without even a pillow under his head. A curve was taken in this position. Then the head-end of the board was raised about five degrees and another curve was taken; the head-end was again raised five degrees and another curve taken, and so on until eleven curves had been taken. With each curve the drum was run rapidly, and a time marker writing fiftieths of a second was used. Five successive pulse-beats from each curve were then selected. The beginning of each pulse, and the crest and trough of the first three waves in each pulse were marked as carefully as possible. The crests and troughs were determined by laying a line along the rises and falls and marking the turning points. Points half way between the turning points were taken as the points desired. These points were then reduced to the level line and marked upon the time tracing by a process similar to that used in studying transmission times. The times from the beginning of the pulse to the first crest, from the first crest to the first trough and so on to the third crest, were counted in fiftieths of a second.

Further, a strip of transparent celluloid, on which lines were ruled one millimeter apart, was taken and one line laid down connecting the beginning and end of the pulse-beat. Using this line as a base, the distances up to the first crest, the first trough, the second crest, the second trough, and the third crest were counted. I then averaged the corresponding quantities for each curve. I will quote three typical sets of averages. In each set, the first quantity given is the pulse length, the second outside of parentheses is the time from the beginning of the pulse to the first crest, the third outside of parentheses is the time from the first crest to the first trough, and so on to the time from the second trough to the third crest. The quantities in parentheses are the elevations of the same points. The first quantity in brackets is the total time from the beginning of the pulse to the crest of the second wave, and the second in brackets is the total time to the crest of the third wave. Curve 4 gave 44.4, 5.5 (4), 3.8 (2.1), 4.1 (3.1), [13.4], 3 (2.2), 5.1 (2.9), [21.4]. Curve 7 gave 43.5, 5.5 (28.8), 4 (18.8), 3.9 (23), [13.4], 3.4 (20.2), 5.3 (21), [22.1]. Curve 11 gave 44.5, 6.1 (33.5), 3.4 (27), 4.2 (35.3), [13.7], 3.4 (30.5), 4.8 (30.7), [21.9].

I reproduce a set of typical pulses from six curves. No. 2 contains part of those marked to count. But, as a rule the record was too much marred by the instruments to be reproduced, and other parts were selected to be printed. It will be seen from the measurements and from the tracings that the different crests were slightly delayed, if anything, as the subject was raised toward a sitting position, but there was no important variation in temporal arrangement. The height of the pulse became greatly increased, the height of the secondary waves from trough to crest did not increase in proportion to the increase in the pulse, in fact, the second trough and following wave became even less prominent. The main skeleton of the pulse on which the secondary waves may be considered erected, seems to be more rounded out when the subject is sitting up, instead of being turned sharply downward immediately after the primary thrust as it is when the subject is lying down, especially when he is lying on his right side.

H., August 1, II, and H., July 26, II (Fig. 77, Plate 60).—These were taken from the second subject by means of the first form of brain plethysmograph. He was sitting up leaning forward. The various troughs and crests are not clear in H., July 26, II. But the general similarity of form to the above curves from the sitting up position is evident.

H., July 26, I, no. 1 and no. 2 (Fig. 77, Plate 60).—The second form of brain plethysmograph was used. In no. 1 the subject was lying down on his back and resting his head on a pillow of medium thickness. In no. 2, his head was raised up at a sharp angle with his body. There is an elevation of the secondary waves, only of less degree than when his body was raised for the records of July 21.

With the second subject sitting up, the elevation of the secondary waves is already so extreme that the change on going to sleep cannot show itself so clearly as with the first subject. But, on the whole, the tendency is toward a still greater elevation.

Recently I have used a third trephined subject K. in a few experiments. The work was mostly concerning the effects of drugs upon the brain circulation. But I wish to refer here to some changes of pulse form in different positions. The trephine was through the front part of the left temporal bone. The first form of brain plethysmograph was used. K 1 (Fig. 78, Plate 61) shows the pulse when the subject was sitting up with his head erect. In K 2 (Fig. 78, Plate 61) he was sitting up with his head tipped as far as possible towards his right shoulder. K 5 (Fig. 78, Plate 61) is from a position sitting up with his head tipped toward the left shoulder. With K 7 (Fig. 78, Plate 61) he was lying down on his back. K 8 (Fig. 78, Plate 61) shows the form when he was lying down on his right side. K f (Fig. 78, Plate 61) was taken during another day's work when the pulse from other positions (all positions were not taken on any one day) was much larger than in the above extracts. The subject was lying on his left side, and an assistant (Dr. Clarke) held his head so that it did not rest on the plethysmograph. The tracing shows a low dicrotic and the broadened, rounded crest which a plugged trephine always tends to cause.

It is found, then, that the effect of position is in the same direction as in the

first and second subjects. The subjects differ from each other in the exact pulse form in any given position, and each subject may show a somewhat different form at different times. But every change that amounts to a lowering of position and the kind of congestion that results from lower position, tends to lower the level of the secondary waves. Any rise of position in any way, causes a rise of the secondary waves.

It may be added that a change of pulse form due to position or sleep lasts as long as the condition which brings it about.

B., June 21, no. 1 and no. 2 (Fig. 79, Plate 61).—These are from the subject B. immediately after a blood-pressure test. The lower curve is a plethysmographic record from the right hand, which had been running continuously and with no definite change of level, or shape and size of pulse, during the whole experiment. The upper curve is from the left wrist, which of course was the one used for the blood-pressure tracing. No. 1 was taken as soon as the pressure was dropped to zero immediately after the test. No. 2 was taken about three minutes later after the tingling of the arm had ceased. During the period between no. 1 and no. 2 there was no measurable change in the level or pulse of the lower curve. On the other hand, the upper tracing fell six centimeters or more, and had to be raised artificially several times, and the pulse became distinctly smaller. This decrease of volume was not due to the escape of venous blood, for the arterial pulse should have increased rather than decreased in size. And it was probably not due to a fall of blood-pressure, for the other hand might be expected to show some effects of such an extreme fall as would have been necessary. We may, therefore, infer that we are dealing with a condition of relaxation[1] of the vessels of the left arm in no. 1, and that they had constricted to more nearly their normal condition in no. 2. With the constriction the dicrotic has fallen and assumed more nearly the position and character it had before the test, which was approximately like that of the lower curve.

W., July 11, no. 1 and no. 2 (Fig. 79, Plate 61).—The blood-pressure apparatus was used in another test that probably has some significance for the explanation of the pulse forms found. Curves were taken from the carotid and from the sphygmomanometer sleeve, along with a time record. In part of them the pressure in the sleeve was only fifteen millimeters; in others it was one hundred and thirty-seven millimeters, which is a little above systolic pressure for the subject (W.) used. In the first case, of course, the sleeve gave what we have called the third type of pulse, and in the second case it gave the second type

The beginning of each pulse, the crest of the primary wave, and the dicrotic notch were carefully marked on both curves. The points were then reduced to level and counted on the time line as before, and the comparative time of each point in the carotid and the sleeve was determined. These times expressed in two-hundredths of a second, were averaged. It was found that when the pressure in the sleeve was 15 mm., the beginning of the pulse in the sleeve was delayed 9.3,

[1] We should, doubtless, refer this to the effects which asphyxial products have been shown to have upon the vessels.

the crest of the wave in the sleeve was delayed 4.5, and the dicrotic notch in the sleeve was delayed 8.2, compared with the carotid. On the other hand, when the pressure was 137 mm., the delay of the beginning was 9.3, of the crest was 2.8, and the dicrotic (if, indeed, this should be called dicrotic) notch in the sleeve preceded the dicrotic notch in the carotid by 5.9. Also, the time from the beginning of the pulse to the dicrotic notch in the sleeve curve, was counted in fiftieths of a second. This time was 15.5 fiftieths when the pressure was 15 mm., and was 12 fiftieths when the pressure was 137 mm. The waves begin at about the same time with the two pressures; but the crest is somewhat, and the dicrotic notch is very much hastened by the high pressure.

No. 1 shows a pulse with low pressure in the sleeve; no. 2 a pulse with high pressure in the sleeve. It will be seen that with low pressure the dicrotic notch is fairly high and the pulse-wave falls gradually; while with high pressure, the dicrotic notch is as low as, or lower than the beginning and end of the pulse.

I. t. (Fig. 79, Plate 61) is not a pulse-beat. The curve is intended to suggest the amount of inertia we must allow for in a pulse form tracing. The level was suddenly raised by driving in the plunger used for artificial regulation. The piston recorder needle rose more rapidly than it is forced to move in the usual pulse curve. The amount of inertia is not sufficient to interfere seriously with any conclusion we shall draw as to pulse form. *R. L.* is a reference line.

The real summary of this chapter will come out in connection with a discussion of general conclusions in the next chapter, and some attempt will be made to explain the pulse forms.

I may add that measurement on the time line showed that the temporal position of the secondary waves within the pulse from the brain is about the same during sleep as during waking; if there is any difference, it is slightly later.

CHAPTER VII

GENERAL CONCLUSIONS AND THEORY

It is not my purpose to review and discuss the exceedingly voluminous literature concerning some of the topics considered. I wish simply to bring out several conclusions that seem to me justified by the results of this investigation.

Huber, Hunter and others have shown that there are nerve terminals in the brain vessels. But it has been suggested that these may be sensory in their nature; and, in any case their mere presence does not necessitate an effective activity. Wiggers has studied the brain in the detached head of a dog, by use of an improved perfusion method. He found that certain drugs, especially adrenalin, caused a change in the outflow. Since adrenalin probably acts only upon the nerve terminals, this fact indicates the action of sympathetic fibers in the brain vessels. He also found that electrical stimulation of the sheath of the carotid gave a decreased outflow, which shows that constrictor fibers run with this artery to the cerebral vessels. These results lead us to look for more active control. So far as we are concerned with the explanation of the sleep process and the effective control of the brain circulation, however, Wiggers' work is insufficient in two respects. In the first place, we cannot say to just what degree the facts in the case of the dog are true in the case of man. In the second place, attempts to demonstrate the activity of vaso-motor nerves in the brain vessels, when the brain was under the influence of the general circulation, have, according to most observers, ended in negative results. We do not know therefore, to what extent, if any, there may be effective activity of cerebral vaso-motors under normal conditions. It is exactly on this point that the results of this research seem to me to offer fairly definite and conclusive evidence. I do not see how we can avoid the conclusion that the brain vessels are not inactive, that they do not follow passively the changes in general arterial and venous pressure, but that on the contrary, they are under the quite definite control of a system of vaso-constrictors, and the center of this control is probably a portion of the general constrictor center in the medulla.

In the first place, we find with sleep a sustained and marked increase in volume of the brain accompanying a fall of general arterial pressure, and the reverse changes with awakening. Both the direct blood-pressure measurements and the study of transmission times show this fact. There are several reasons for deciding that this change in volume cannot be venous congestion. Firstly, there is no analogous change in the jugular curve. Secondly, the first form of brain plethysmograph gives the above result in all positions with even greater clearness than the second form; and this with a pressure, due to tension of the rubber, which is higher than any pressure from venous congestion could probably ever attain.

Venous congestion could not ordinarily have overcome the tension of the rubber, which was far above the usual venous pressure. Thirdly, the rise of volume with sleep is accompanied by an increase in the size of arterial pulse in the brain; the fall of volume with waking is accompanied by a decreased size of pulse in the brain, while the rise of brain volume due to compression of the jugulars is accompanied by a decreased arterial pulse in the brain. Fourthly, the pressure in the jugulars was insufficient to give any trace of a venous pulse when the subject was sitting propped up, or when he was sitting up leaning forward; and yet, in both positions, and with both forms of brain plethysmograph, the brain showed the same reactions in volume and size of pulse, as when the subject was lying down.

Disturbances during sleep result in a rise of pressure with a fall of brain volume and decreased size of pulse from the brain; again, the blood-pressure measurements and the study of transmission times agree in this conclusion. Furthermore, with the second subject, the Traube-Hering wave in the brain is opposed to the wave in general arterial pressure, and the breathing wave is at least partly so. For reasons similar to those above, these volume changes cannot be venous. The pulse is largest at the crest and the results were obtained especially with the first form of brain plethysmograph. If there is any change in the jugular curve, it is, in general, opposed to that in the brain. That the Traube-Hering wave in brain volume when the subject is sitting up is the same as when he is lying down, is attested by the fact that it is always parallel to that in the hand.

I can see no reasonable escape from the conclusion that there is an active, effective vaso-motor control of the brain vessels in man under normal conditions. Other facts indicate the same thing. With the first subject lying down awake, stimuli gave a rise of brain volume and decreased size of pulse. This rise was doubtless a result of increased blood-pressure. But the rise with sleep in the same position is accompanied by an increased pulse. It does not seem possible that the change in volume is due to the same factors in both cases. Furthermore, reactions in the brain while awake show no definite and consistent change in pulse form. Rise of volume with sleep invariably tends to cause a rise in the level of the secondary waves with no appreciable change in their temporal relations; when the position of the secondary waves is low at the start, this rise in level is very marked. The fall with awakening gives the opposite result. Now, in the study of pulse forms from the hand following blood-pressure tests, we have found a condition which is probably one of local relaxation giving a higher position of the secondary waves, and constriction causes a return of these waves to their original position. Also, the most consistent change in pulse form that I have found with reactions while awake was a lowering of the position of the dicrotic in curves taken with the finger plethysmograph. This change was not always found, but often was. In this instrument more than anywhere else we probably have a vaso-constriction of the small arteries with comparatively little interference of the larger vessels which do not constrict. An explanation of these form changes,

and a discussion of their relation to those found in different positions, will make the matter clearer; but a comparison of the facts stated, certainly suggests that local constriction gives a lower level of secondary waves; local dilation gives a higher level, and therefore the brain vessels relax with sleep and actively constrict with awakening. All the facts without exception consistently lead to this conclusion.

We might raise the question whether this definite relaxation with sleep, and constriction with awakening can be brought about in any way by the changed breathing. We shall discuss the periodic alternation of restricted and freer breathing in connection with the Traube-Hering wave. In the second and third types, the depth of breathing was a little increased, if anything, in sleep, and there was regular snoring in the second. But artificial increase in depth, and snoring during the waking condition gave a fall of the brain. The mere change from abdominal to chest breathing causes no change in the brain. Changed condition of the blood from changed breathing, if there is any such change, is doubtless not in any way responsible.

We found in the study of volume changes, that the brain curve was often held up or even raised a little for a few pulse-beats before a fall in response to a disturbance or awakening. Likewise, in the study of blood-pressure and of transmission times, it was in the majority of cases seen that the rise of blood-pressure began one or two pulse-beats before the fall of brain volume. These facts indicate that the reaction time of the brain vessels is distinctly longer than that of the main vaso-motor mechanisms outside the brain. The cause of the temporary hold-up and of the rise of pressure before the fall in the brain begins, is to be found in the quicker response of the other regions. We have an analogous case in the fact that there is often a rise with smaller pulse, in the hand for three or four pulse-beats before the fall begins in response to very strong stimuli while the subject is awake. We may suppose that both hand and brain react more slowly than the great splanchnic area, the brain most slowly of all, perhaps. It should be stated that the change in either hand or brain may sometimes begin before the rise in blood-pressure.

A comparison of the reactions to stimuli while the subject is asleep and while he is awake, brings out an interesting difference between the vaso-motor control in the brain and in the periphery. Disturbances while asleep consistently give a fall in the brain which we have shown to be due to vaso-constriction. Disturbances while awake consistently give a rise of volume of the brain, although the effect was not so great in the second subject as in the first. These statements hold in all positions of the subjects and in curves with either form of brain plethysmograph. When the subject is sitting up, this increase during waking condition is accompanied by increased pulse, but neither the reactions while awake sitting up nor those while awake lying down, give the characteristic pulse form changes of sleep. Neither the reaction while asleep nor that while awake can be due to venous congestion, and yet the cause of the one must be different from that of the other Doubtless, the main or only factor in the increase while awake is

the rise of blood-pressure which is brought about by constriction of other regions. The pulse does not increase, usually decreases while lying down because the vessels are approaching a practical limit of distensibility. We noticed also that the pulse is generally smaller during the first part of a reaction period while awake, than it is at the same level of volume during the last part. We might go farther and infer with some probability that there is a tendency of the brain vessels to constrict and lower the limit of distensibility during reactions while awake, especially at first; but this tendency is overcome by the rise of general arterial pressure.

We reach the conclusion, then, that the brain vessels relax on going to sleep and constrict on awakening with relatively great activity. There is a fall even when the subject is awakened with a start by a strong stimulus, and in spite of a large rise of blood-pressure. Correspondingly, few reactions while awake even compare with the rise with going to sleep. On the other hand, the ordinary stimuli of the waking condition seem sufficient to cause the brain to constrict nearly to its limit, and to remain in that condition; so that the tendency to further constriction with stimuli while awake is relatively powerless and is overcome by the rise of pressure due to constriction of other regions which do not show such a limit of constriction.

The increase in brain volume due to holding the breath and the decrease due to increased breathing are probably primarily the results of changes in general arterial pressure. I have not evidence enough to say what local activity may be present, and this subject deserves further study as soon as there is opportunity.

It has been suggested that the vaso-motors in the brain may react differently in different areas according to the nature of the stimulus and consequent activity of the different parts. This can only be determined on a person with at least two trephines in different locations. But I am inclined to doubt it because of the indications of some tendency to constrict in response to stimuli that certainly involved the activity of the area under the trephine.

The respiratory wave in the brain volume was found to be greater during sleep than during the waking condition, and greater with snoring than with freer breathing. There is a large breathing wave in the heart-rate, the increase in rate beginning soon after the beginning of inspiration, the decrease in rate beginning soon after the beginning of expiration. The blood-pressure tests (and with less certainty the transmission time tests) showed that the respiratory wave in blood-pressure begins its rise anywhere on the rise of volume. In many records the rise in pressure begins just before the crest of volume, and the greater part of the rise in pressure coincides with a falling volume. It seems possible that the trough of pressure more nearly corresponds to the trough of volume during sleep than during waking condition. I cannot avoid the conclusion that vaso-motor changes play an appreciable part in the respiratory wave, notwithstanding the usual assumption to the contrary. Inspiration is the period of dilation, expiration is the period of constriction. If there is a nearer correspondence of pressure and volume waves during sleep, it probably means that a greater part is played by

pressure changes in the chest on account of snoring, and by the unusually large wave in the heart-rate.

It was found that the Traube-Hering wave is parallel, or nearly so, in the brain and hand of each of the three trephined subjects used. With the second subject, this wave is uniformly active in brain and hand; i. e., the fall corresponds to rising pressure, the rise corresponds to falling pressure. So far as could be inferred from the transmission curves, which were not very certain, the wave is passive in the first subject except when accompanied by periods of alternately restricted and freer breathing in sleep. During the transition as the subject goes to sleep, the wave is not always parallel in brain and hand. It is certainly passive in one subject (B.); and is partly passive, partly active in another (W.). Of course, in these cases we do not know whether the waves are parallel in brain and hand. But in any case, any investigation which attempts to establish a relation between the Traube-Hering wave and other phenomena can have little certainty without a blood-pressure test which will show the kind of wave dealt with.

We found the Traube-Hering wave of the waking condition giving place to the wave with periodic changes of breathing during sleep. These breathing changes cannot be looked upon as the cause of the volume changes. While awake, restriction of breathing caused a rise in brain volume because of increased blood-pressure, and deeper breathing caused a fall because of the lowered blood-pressure. In sleep, the restricted period is accompanied by relaxation of brain vessels and lower blood-pressure, and freer breathing is accompanied by constriction in the brain and higher blood-pressure. Furthermore, the rise of volume when the breath is held in waking, begins some time after the beginning of restricted breathing, and it reaches its crest a couple or more breaths after the return of freer breathing. During sleep, the rise of brain volume begins early; the fall begins sometimes before, sometimes simultaneous with, more often after the abrupt beginning of freer breathing. But the blood-pressure and transmission time tests show that constriction in other regions usually begins a little before the brain and generally as soon as or earlier than the freer breathing. In the third type of breathing, the transition is more gradual and the change in breathing is nearly always somewhat delayed, compared with the corresponding phase of volume. The breathing change, therefore, cannot be primary, although an abrupt breathing movement may possibly act like any other stimulus. Lastly, a vaso-motor wave persists when the breathing change is entirely absent. We must suppose that the vaso-motor wave is primary and the breathing center is stimulated by it. It is possible that an accumulation of carbon-di-oxide during restricted breathing tends to stimulate both centers. The Traube-Hering wave during waking condition seems to be increased by conditions following inhibited breathing. It is never so large at other times in sleep as when we find the first type of breathing. It is not improbable that the wave represents mainly the attempt of the vaso-motor center to adapt itself to chemical stimuli such as carbon-di-oxide. It might be noted in this connection that we find an active wave in the brain volume when the subject is awake, and an *external* stimulus would give a passive rise of volume.

The heart-rate curves indicate that the heart is accelerated during the inactive phase of the Traube-Hering wave, and slowed during the active phase. This relation is probable, although further work will be necessary in order to speak with certainty. It is certain that we usually get a temporarily slowed heart with periods of disturbance and freer breathing with vaso-constriction; and a faster heart as a rule with periods of restricted breathing and vaso-dilation during sleep. But during waking condition, restriction of breathing causes a slowed heart-rate, and increased breathing causes a faster heart-rate. It is probable, then, that the vaso-motor process rather than the accompanying breathing change, is the cause of the corresponding wave in the heart-rate, as it is, of course, when there is no change in the breathing.

It looks as though the center for vaso-motor control in the brain is a part of the general center in the medulla, and the activities of the breathing and vaso-motor centers influence each other and also the inhibitory center of the heart. Activity of the vaso-motor center perhaps stimulates both the others. Activity (inspiratory) of the breathing center inhibits both the others.

We may get a suggestion for the explanation of the pulse form changes from a consideration of the pulse from the sphygmomanometer sleeve. With very high pressures in the sleeve, we found a small pulse in which the fall from the primary rise to the end was fairly gradual. Von Recklinghausen has explained this as due to the fact that the neighboring tissues partly support the edge of the sleeve and enable the changes in blood-pressure with this assistance to impress it as though these changes were slight variations in the supporting force. With somewhat lower pressure in the sleeve, we obtain a pulse in which the primary rise is quickly followed by a fall to a trough often lower than the beginning and end of the pulse; this is the second type of pulse. In the preceding chapter, this pulse was compared with the third type obtained when the pressure in the sleeve is below blood-pressure. It was found that the two types begin about the same time after the carotid; and the dicrotic notch in the third type was nearly as much after the corresponding notch in the carotid. But in the second type, the dicrotic notch preceded the notch in the carotid, so that the length of the systolic wave was shortened by 3.5 fiftieths of a second. We may suppose that in the third type the wave is broadened by reflection from the terminals in the hand, and that in the second type this reflected wave is of course absent. Such a factor doubtless plays a part. But the reflection of the sharp rise of the systolic wave would be mainly concerned, and this should broaden and delay the crest approximately as much as it displaced the dicrotic notch. Instead of this, we find the crest hastened comparatively little in the second type, the difference consists mainly in the very rapid fall to the dicrotic (?) notch. It may be added that the pulse changes toward the third type when the pressure is sufficiently relaxed to allow an inrush of blood into the lower arm; and yet there is no back reflection from the hand then, as shown by the simple step-up form of pulse from the lower arm. This fact and the extremely low dicrotic notch of the second type combined with a systolic wave that is higher than that in the first type, suggests that it is against

the clear-cut closure of the artery by the sleeve that we have the most definite reflection. The momentum of the primary wave may raise the sleeve somewhat, and the rebound gives a quick fall to a very early and low dicrotic (?) notch.

Now we have found that constriction in an area tends to lower the level of the secondary waves in the pulse from that area, by causing a quick fall after the crest in the skeleton (omitting secondary waves) form of the pulse. Relaxation gives the opposite result. As I think of it, the constriction gives a higher coefficient of elasticity in the area and leads to a quick rebound after the primary wave. Similarly a lower position (lying down, etc.) of the area causes a local rise of pressure, a stretching of the vessels toward their limit of distensibility, a higher coefficient of elasticity and a sharp reflection with consequent lowering of the latter part of the pulse. A higher position (sitting up, etc.) gives a lowering of a coefficient of elasticity in the area, less reflection, and therefore a pulse more rounded out and with higher level of the secondary waves. When the change in volume is brought about by a change in general arterial pressure, or even when there is a change in arterial pressure approximately proportional to the vaso-motor change, the coefficient of elasticity outside the area concerned is modified also perhaps even more than that in the area. Under these circumstances the pulse form may not be definitely changed. It is the distinct change in coefficient of elasticity in a given area, compared with that in the general system, that determines a marked difference in reflection and pulse form.

Of course, other factors, especially the relative temporal position of the secondary waves within the total wave, determine the pulse form throughout the system. In spite of the excellent arguments of Von Kries, Von Frey and others, however, it seems to me probable that reflection influences the pulse form more in the above way than by creating definite secondary waves which then travel into other regions. Von Kries states that the tachograph shows greater reflection with elevation of the arm. It seems to me that his plates show less reflection then, in proportion to the previous inflow. The similarity of my interpretation to that of Von Recklinghausen is obvious, although I did not know his work in time to help me in taking and working up my own records.

Both change of position and vaso-motor reactions seem to cause greater change in the pulse form from the brain than in that from other regions. We might infer that both these processes give a greater change in coefficient of elasticity in the brain vessels than in others; but I know no explanation for this difference.

According to the results of this investigation, we certainly cannot adopt an anæmia theory of sleep. I once thought it possible to explain it as due to separation of dendrites and axones by expansion of the cerebral vessels. There are at least two reasons for giving up this view. In the first place, there are large increases in brain volume with stimuli while awake. These are usually less than the volume change with sleep, to be sure; but they are large enough to be significant and they certainly show no tendency to cause sleep. In the second place, we have found definite evidence that the circulation change lags behind the mental process. The relaxation of the brain vessels with sleep, and their con-

striction with awakening, should therefore be looked upon as an effect rather than as a cause of the sleep process. We must make use of other facts about sleep to find an explanation.

Several writers have reported a more or less regular curve of sleep. The maximum depth is reached at the end of the first hour or so after beginning of sleep; and then the curve (representing the amount of stimulus necessary to awaken the sleeper) falls rapidly at first and slowly later until awakening.

It is a frequently stated fact that the experience of sleepiness and the process of going to sleep are subject to suggestion and to habit. Suggestion means only the getting of an idea in mind. Probably even verbal suggestion can sometimes place a person in an attitude favorable to sleep. We know very little of the circulatory and other conditions that prevail during hypnotism. So far as they have been studied, they are different from those that prevail during sleep. But presumably the mental content, so to speak, of hypnotism might be of various kinds, and might consist of the experience of sleep or of an opposite activity. I am inclined to think that this subject would repay investigation. At any rate, the oncoming of sleep may be greatly influenced by one's surroundings. This does not always mean that sleep is promoted by withdrawing from external stimuli; one who is accustomed to sleep much under the influence of certain external stimuli may demand their presence. Sleep is promoted by the situation in which we have really become accustomed to sleep. One may learn to sleep best in a given environment, just as one may learn to give attention to anything, or to work best in a given environment. One may even learn to sleep in a position which requires the continued contraction of a certain set of muscles in order to maintain his balance. It may be more difficult to wake up than to keep awake sometimes, just as it is difficult to shift attention when it is once absorbed in a subject. Sleep is controlled by conditions similar to those which control attention generally. Sleep and sleeplessness are mental processes.

What then do we find if we attempt to analyze it introspectively? Various people describe it in terms that mean essentially the same thing. We experience a "yielding to the force of gravity," "yielding to a heaviness," "becoming lost in rest sensations or feelings." These sensations seem to come from muscles all over the body. The sensations which we receive from the tired muscle are undoubtedly of different character from the strain sensations we receive from the acting muscle. Whether the two are due to different terminals, or different ways of acting of the same terminals, we do not know. The fatigue sensations seem to result from chemical stimuli (waste products) given off by the tissues. They often appear to be more intense after the muscle has relaxed than before. Whether the removal of the self-massage and the greater or less cessation of the strain sensations actually allows a more intense stimulation of fatigue sensations then, or whether they are merely more noticed then, it is as yet difficult to say. Yoakum points out that they develop sooner in the acting rigid muscle than in the periodically contracting muscle. Although the nerve terminals are only in the muscles, apparently, they may probably be excited also by substances thrown into the circulation from other tissues.

As we go to sleep, then, we become absorbed in a mass or complex of fatigue sensations. These tend strongly to inhibit other processes, especially motor activity and consciousness of strain sensations from the muscles. The subject "can't bring himself to do" a thing. When this tendency is yielded to, the subjects speak of the experience as one of "feelings" or "sensations" of "rest." Next, probably the skin sensations, as being closely connected with motor reflexes perhaps, are inhibited. Last of all, as a rule, the auditory sensations seem to disappear, and they arouse motor activity and interfere with the general condition of rest, least directly of any. In short, the content of sleep consists of a group of sensations of "fatigue" or "rest." Sleep is a more complete rest. The process is a dominance of an organized group of these sensations. Such sensations from one part are associated with those from another. It is not that the sensations are only aroused at the time of sleep, of course, but that they become dominant in attention as any other group of experiences may be dominant in attention. This dominance is promoted by the intensity of the sensations themselves and by other conditions of attention.

That the intensity of sleep tends toward a maximum some time after sleep begins, may be analogous to the inertia of attention to other things. After two or three hours, sufficient waste products may be thrown off, that there is less actual stimulation of fatigue sensations, and less resistance to disturbance by other processes. But the relatively small value of sleep broken up in short periods, suggests that the real anabolic processes do not become very effective until after this time. Over-fatigue may be injurious to sleep, to be sure, but because of the mental excitement or because the excited condition of the muscles continues to arouse strain and pain sensations, and prevent relaxation. Lastly, learning to sleep in a position involving strain of some set of muscles seems to mean the forming of an association between the strain and a condition of rest of other parts. Naturally such sleep is not so beneficial.

Under such conditions of inhibition by a group of sensations of rest, what other processes do arise and constitute dreams, will of course have the uncertain and little controlled character of the "fringe of consciousness" when attention is nearly dominated by any other set of experiences. Naturally also, they will tend, as the facts cited in the second chapter suggested, to prove a disturbance of sleep, not an organic part of it.

The muscular relaxation and inhibition of elaborate cerebral and other nervous activity leads to a removal of much of the sensory stimulation of the vaso-motor center and a consequent tendency to relaxation. The brain vessels under the influence of this stimulation have remained constricted during the waking condition nearly to the limit they are capable of, and show the most marked and constant relaxation with sleep. If any special utility is to be assigned to this fact, it may be that the effective building up of energy-giving substance in the brain requires greater circulation than is demanded by other parts. Professor Lombard has suggested that the constriction with waking condition may be protective, preventing too much compression of cerebral cells by higher blood-pressure. During sleep this is unnecessary and we find relaxation.

This relaxation apparently tends to bring with it a decrease of breathing activity at first, which gives too little ventilation. This would probably stimulate all the centers. The first type of breathing would be a result of the attempt of the vaso-motor and breathing centers to adjust themselves to each other with relaxation of the vaso-motor, and to the carbon-di-oxide content of the blood. In this adjustment, it seems to be the chest that takes up the activity mainly; there remains a decreased abdominal breathing. Possibly we might assume that the chest and abdominal breathing are controlled by different parts of the respiratory center, and that the part which controls the chest is not so near the vaso-motor center as that which controls the diaphragm, and not so much influenced by the vaso-motor relaxation.

APPENDIX

THE INFLUENCE OF SOME DRUGS UPON THE CIRCULATION DONE IN COÖPERATION WITH CORWIN S. CLARKE, M.D.

In these experiments the attempt was made to use the methods which have been developed in the study of the circulation and sleep to investigate the effect of certain drugs upon the circulation. The subject was a young man who had recently undergone a Gasserian ganglion operation, the trephine for which was through the front part of the left temporal bone. The form of the pulse through this trephine has already been referred to, in the chapter on pulse form.

The first form of brain plethysmograph (cup covered with thin rubber to which a cork plate is attached) was used in all tests with this subject. New cork plates were made, of course, to fit the trephine. The edges of the instrument were held firmly against the bone by means of a broad bandage tied horizontally around the head. The cavity of the cup was connected to the largest size of piston recorder. No tests were made of the influence of the scalp circulation on the record, since the experiments with the first and second subjects had shown that the pulse and changes in the scalp are negligible in comparison with those in the brain. The principle of the Hallion-Comte plethysmograph was used to record the hand volume. The bulb was connected to a medium-sized piston recorder. The chest breathing was recorded by a Marey pneumograph connected to a Marey tambour. In all this work the subject was sitting up, and was in another room on the opposite side of the wall from the recording apparatus. Dr. Clarke gave the stimuli, and also pressed a key which indicated on the drum places where a significant report was to be made.

On account of the hesitancy of the subject to take the drugs, only a few experiments could be performed. Two tests were made with amyl nitrite, one with nitroglycerin, and one with adnephrin. We shall next reproduce and describe the results with amyl nitrite.

K., November 25, I (Fig. 80, Plate 62).—The diameter is multiplied by three-fourths. The curves from the top down are the chest breathing, the indicator line, the hand volume and the brain volume. A portion of the breathing curve at the start was lost because the tambour was not pressing firmly enough on the paper. At *a*, the glass bulb was broken and the subject began to breathe the amyl nitrite. At *2′*, the subject said, "Pretty near done with that one, Doctor?" Dr. Clarke reported that his breathing was labored as if excited. At *b*, the nitrite had become practically exhausted, and the bulb was removed. At *3*, the subject made a remark. At *4* and *5*, he swallowed. It will be seen that the brain volume began to rise after a few pulse-beats and was dropped twice artificially. The size of pulse from the brain also became larger. Counting the number of pulses in a

given space, shows that the heart-rate increased rapidly. This may be responsible for a hyperdicrotic pulse in the hand at times later in the record. Just before *c*, the low position of the dicrotic in the hand curve without a corresponding volume or heart-rate change, indicates that the blood-pressure has fallen distinctly. At *c*, a very marked rise in the hand curve began. The needle was dropped several times artificially. In spite of the low dicrotic in the hand at *c*, the secondary waves in the brain pulse seem to be somewhat higher at this point, although the pulse form is not clear. The brain volume reached its crest just after *2'* and began a rapid fall with decreasing size of pulse. The sudden rise in the brain at *e* is doubtless due to movement; that at *d* may be. The rise of volume in the hand continued irregularly until *e*. After *e* the hand curve fell rapidly, while the fall in the brain had become comparatively slow.

K., November 25, II (Fig. 81, Plate 63).—The order of the curves is the same as in the preceding extract. The nitrite was given from *a* to *b*. In breaking the glass bulb a loud noise was made and the subject jumped. This is probably responsible for the break in the brain record. At 5_1, 5_2, 5_3, 6, 7, 8 and some other points the subject swallowed. But such acts seem to have no effect upon the circulation curves. The breathing became slower and deeper. The heart-rate was increased considerably. The brain volume began to rise soon after the stimulus began, the curve was dropped twice artificially, and reached its crest at about the time the stimulus ceased at *b*. After the first part of the rise, the pulse became smaller from the brain. This probably indicates a plugging of the trephine as in cases found during sleep. During the fall after the crest in the brain, the pulse first became larger and then smaller. The brain and hand curves interfered under 5, and were changed artificially. The rise with larger pulse in the hand did not begin until *c* and reached its crest at *6*, again distinctly later than the crest of the brain curve. The change in the dicrotic in the hand pulse before *c* indicates that the blood-pressure had already fallen markedly. No tests were made to show accurately the temporal position of the dicrotic in the pulse wave. But in the original of this record as accurate measurements as possible were made on the scale in the eyepiece of a microscope which was mounted so that it could be moved by a screw adjustment. The distance from the beginning of the pulse to the dicrotic was measured. This distance appeared to be greater at *c* than during normal, and still greater towards *6*, a result with lowered pressure. Such a delay, combined with a more rapid pulse would lower the dicrotic. In spite of this, the secondary waves in the brain pulse during the period of high volume, occupy a relatively high position. After *d* they assume a distinctly lower position. It is not so clear whether a similar statement would be true of the hand. Such a high position of the secondary waves may be explained as due to the relaxed vessels and decreased reflection. This explanation is consistent with the theory of pulse form developed on pp. 75 ff.

We find, therefore, that the brain volume is markedly increased under the influence of amyl nitrite, in spite of the lowered blood-pressure which the drug brings about. The brain vessels clearly relax. This relaxation begins very

quickly. Relaxation in the hand begins more slowly, but the high volume of the hand continues after that of the brain. The quick response in the brain is similar to the quick flush of the face.

In the test with nitroglycerin, $^{1}/_{150}$ gr. was injected into the arm. We shall not reproduce the entire record although it was fairly successful. The injection itself acted as a temporary stimulus of course. The effects of the drug began before the stimulus reaction had disappeared. In K., November 26, II (Fig. 82, Plate 63), we reproduce a section showing the condition before the stimulus was given, and another taken from near the end of the record. The total effect had been a fall of about 3 cm. in the level of each circulation curve, which change had been compensated for artificially. The size of pulse from the hand was greatly decreased. There was no constant change in the size of pulse from the brain. It is noticeable that in the first extract before the stimulus, the larger pulse occurs at the crest of the Traube-Hering wave in the brain, while in the second extract the larger pulse is at the trough of the Traube-Hering wave; but without a continuous blood-pressure record, it would be useless to try to explain this. The dicrotic was unusually low, and the pulse unusually fast in the first extract; the dicrotic was still lower in the second. Mentally, the subject was excited at the start by the idea of the injection coming, and this probably modified the reaction.

It is to be regretted that we have only one partially successful record of nitroglycerin. The difference in the reaction to amyl nitrite and nitroglycerin seems to be striking and is of importance. But the results with nitroglycerin are not so certain as those with amyl nitrite.

The adnephrin was given through the mouth. The result was not very definite, but there was apparently a rise in volume of both brain and hand. The record was not successful enough to reproduce.

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